

numbers below by 3.664.

s and 8 fCO<sub>2</sub>-products that reproduce the observed mean ocean sink of the as the half of the difference between GOBMs and data products in the period variable with the ocean model results and to satisfy the definition of the ocean

arsening algorithm in a global eddy-admitting ocean biogeochemical model. Jour biogeochemistry in the coupled ocean–sea ice–biogeochemistry model FESOM2. carbon and ecosystem studies.

of Poleward Ekman Transport and Influence on Atmospheric CO<sub>2</sub>, Global Biogeo horizontal resolution of an ocean model on carbon circulation in the North Pacific C. Evaluation of NorESM-OC (versions 1 and 1.2), the ocean carbon-cycle stand-system revealed using a global ocean biogeochemical model. Biogeosciences, 18 each- anisms governing interannual variability in upper-ocean inor- ganic carbon sy rrient Inputs May Alleviate Effects from a Changing Physical Climate on the Ocean t, D., Yan, H., and Vohralik, P. F.: The carbon cycle in the Australian Community

and air–sea CO<sub>2</sub> fluxes over the global coastal and open oceans, Biogeoscience ation-based reconstruction of surface ocean inorganic carbon variables. J. Ocean achine Learning to Merge Global Models and pCO<sub>2</sub> Data, J. Adv. Model. Earth Sy decadal air-sea CO<sub>2</sub> flux variability, Global Biogeochem. Cycles, 30, 1396–1417, chine learning with modelled variable trends. Front. Mar. Sci. 9:989233. doi: 10.3 ical Cycles, 38, e2024GB008127. <https://doi.org/10.1029/2024GB008127> air CO<sub>2</sub> flux variations 1957–2020 and their relation to environmental drivers, Bio global surface ocean CO<sub>2</sub> estimates using a machine-learning ensemble (CSIR-M r-Murphy, L.: Revised estimates of ocean-atmosphere CO<sub>2</sub> flux are consistent with

|                 | 0.265 | 0.229       | 0.279      | 0.378          |
|-----------------|-------|-------------|------------|----------------|
|                 | 7     | 8           | 9          | 10             |
| NEMO-PlankTOM12 |       | CESM-ETHZ   | MPIOM-HAM  | ACCESS (CSIRO) |
| 0.888243357     |       | 1.254454545 | 0.73483217 | 1.103422378    |
| 0.724004983     |       | 1.193484572 | 0.73578741 | 1.103255813    |
| 0.718766608     |       | 0.915514598 | 0.70574266 | 1.020089248    |
| 0.706528234     |       | 0.984544624 | 0.7476979  | 1.195922684    |
| 0.95228986      |       | 1.08557465  | 0.89965315 | 1.372756119    |
| 0.901051486     |       | 1.219604677 | 1.06260839 | 1.348589554    |
| 1.034813112     |       | 1.343634703 | 1.16356364 | 1.61742299     |
| 0.920574738     |       | 1.281664729 | 1.11051888 | 1.500256425    |
| 0.862336364     |       | 1.051694755 | 1.00547413 | 1.30408986     |
| 0.95809799      |       | 1.174724781 | 1.08542937 | 1.534923295    |
| 1.160859615     |       | 1.254754808 | 1.09638462 | 1.655756731    |

|             |             |            |             |
|-------------|-------------|------------|-------------|
| 0.933621241 | 1.039784834 | 1.07233986 | 1.368590166 |
| 0.914382867 | 1.13781486  | 1.2162951  | 1.608423601 |
| 1.263144493 | 1.471844886 | 1.31325035 | 1.983257037 |
| 1.073906119 | 1.324874913 | 1.34820559 | 1.732090472 |
| 0.911667745 | 1.134904939 | 1.35516084 | 1.687923907 |
| 0.747429371 | 1.067934965 | 1.41111608 | 1.583757343 |
| 1.180190997 | 1.289964991 | 1.40707133 | 1.902590778 |
| 1.324952622 | 1.428995017 | 1.54902657 | 1.916424213 |
| 1.239714248 | 1.450025044 | 1.50998182 | 1.917257649 |
| 1.316475874 | 1.38905507  | 1.24493706 | 2.097091084 |
| 1.5142375   | 1.700085096 | 1.61389231 | 2.266924519 |
| 1.390999126 | 1.561115122 | 1.60884755 | 2.179757955 |
| 1.632760752 | 1.700145149 | 1.6008028  | 2.43659139  |
| 1.833522378 | 1.933175175 | 1.72275804 | 2.585424825 |
| 1.574284003 | 1.626205201 | 1.73171329 | 1.84325826  |
| 1.445045629 | 1.558235227 | 1.71466853 | 2.204091696 |
| 1.377807255 | 1.543265253 | 1.72262378 | 2.280925131 |
| 1.525568881 | 1.72429528  | 1.66557902 | 2.550758566 |
| 1.451330507 | 1.725325306 | 1.68953427 | 2.178592002 |
| 1.485092133 | 1.541355332 | 1.79048951 | 2.058425437 |
| 1.598853759 | 1.708385358 | 1.83144476 | 2.218258872 |
| 1.834615385 | 1.872415385 | 1.8164     | 2.417092308 |
| 2.00837701  | 2.055445411 | 2.10035524 | 2.556925743 |
| 1.953138636 | 1.987475437 | 2.03631049 | 2.459759178 |
| 1.761900262 | 1.777505463 | 1.90226573 | 2.233592614 |
| 1.637661888 | 1.81253549  | 1.89022098 | 2.386426049 |
| 1.691423514 | 1.810565516 | 1.84317622 | 2.278259484 |
| 1.82718514  | 1.972595542 | 1.75313147 | 2.75909292  |
| 1.880946766 | 2.003625568 | 1.78908671 | 2.729926355 |
| 1.619708392 | 1.725655594 | 1.93104196 | 2.29275979  |
| 1.465470017 | 1.615685621 | 1.9419972  | 2.267593226 |
| 1.528231643 | 1.587715647 | 1.80795245 | 2.267426661 |
| 1.962993269 | 2.025745673 | 2.07790769 | 2.712260096 |
| 1.949754895 | 2.178775699 | 2.11686294 | 2.841093531 |
| 2.005516521 | 2.071805726 | 2.10381818 | 2.863926967 |
| 1.947278147 | 2.155835752 | 2.10677343 | 2.904760402 |
| 2.129039773 | 2.179865778 | 2.17972867 | 3.302593837 |
| 2.014801399 | 2.078895804 | 2.17968392 | 3.144427273 |
| 2.056563024 | 2.04392583  | 2.21663916 | 3.229260708 |
| 2.16032465  | 2.146955857 | 2.15759441 | 3.205094143 |
| 2.010086276 | 2.144985883 | 2.21854965 | 3.153927579 |
| 2.168847902 | 2.150015909 | 2.3055049  | 3.173761014 |
| 2.133609528 | 2.316045935 | 2.34446014 | 3.313594449 |
| 2.188371154 | 2.328075962 | 2.42641538 | 3.268427885 |
| 2.33313278  | 2.365105988 | 2.50837063 | 3.40726132  |
| 2.447894406 | 2.493136014 | 2.54132587 | 3.542094755 |



|             |             |            |             |
|-------------|-------------|------------|-------------|
| 2.461656031 | 2.59416604  | 2.55528112 | 3.421928191 |
| 2.324417657 | 2.348196066 | 2.43023636 | 3.327761626 |
| 2.344179283 | 2.427226093 | 2.48919161 | 3.522595061 |
| 2.343940909 | 2.415256119 | 2.43214685 | 3.449428497 |
| 2.287702535 | 2.429286145 | 2.6001021  | 3.450261932 |
| 2.183464161 | 2.237316171 | 2.65705734 | 3.329095367 |
| 2.188225787 | 2.287346198 | 2.59501259 | 3.321928802 |
| 2.517987413 | 2.436376224 | 2.55796783 | 3.595762238 |









1990s. UExP-FFN-U not used for the fCO<sub>2</sub>-products average. Cite as: Friedlingstein et al. 1990-2001 (inclusive). This ensures no artificial jumps occur in 1990 when the data from the Global Carbon Project carbon sink used in the Global Carbon Project

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6.723772578

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| fCO <sub>2</sub> -products |                   | CMEMS-LSCE- |
|----------------------------|-------------------|-------------|
| Multi-model mean           | Model Spread (sd) |             |
| 0.85596014                 | 0.283010204       |             |
| 0.84734927                 | 0.261289234       |             |
| 0.7273384                  | 0.253649164       |             |
| 0.804927531                | 0.265731944       |             |
| 0.979816661                | 0.250214528       |             |
| 1.110205791                | 0.220671988       |             |
| 1.209994921                | 0.25808497        |             |
| 1.171884052                | 0.249628748       |             |
| 1.008273182                | 0.250569223       |             |
| 1.098562312                | 0.266441682       |             |
| 1.212851442                | 0.244930678       |             |

|             |             |             |
|-------------|-------------|-------------|
| 1.061840573 | 0.238439541 |             |
| 1.139629703 | 0.285545282 |             |
| 1.419618833 | 0.278828563 |             |
| 1.308907963 | 0.302005833 |             |
| 1.236597094 | 0.325091911 |             |
| 1.154586224 | 0.34115788  |             |
| 1.364675354 | 0.319011381 |             |
| 1.472864484 | 0.301117615 |             |
| 1.457853615 | 0.275289525 |             |
| 1.424642745 | 0.29975917  |             |
| 1.744631875 | 0.282850457 |             |
| 1.663521005 | 0.2953244   |             |
| 1.772510135 | 0.295136835 |             |
| 1.968099266 | 0.297706895 |             |
| 1.745988396 | 0.239013623 |             |
| 1.659577526 | 0.342165631 |             |
| 1.726166656 | 0.344107609 |             |
| 1.828655787 | 0.328055382 |             |
| 1.735644917 | 0.30974636  |             |
| 1.710934047 | 0.290082533 |             |
| 1.820623177 | 0.271575177 | 1.905596564 |
| 1.979012308 | 0.232830416 | 2.039494126 |
| 2.142601438 | 0.231948056 | 2.067673974 |
| 2.113490568 | 0.232271883 | 2.179659657 |
| 1.902879698 | 0.281596163 | 2.194030354 |
| 1.939268829 | 0.271468167 | 2.187699805 |
| 1.936257959 | 0.240781415 | 2.150976882 |
| 2.060547089 | 0.295157589 | 2.309210968 |
| 2.122636219 | 0.293616215 | 2.181567485 |
| 1.92002535  | 0.326578965 | 2.061701016 |
| 1.83401448  | 0.333590779 | 2.101306663 |
| 1.75520361  | 0.331510239 | 2.098720593 |
| 2.16019274  | 0.286999192 | 2.331509101 |
| 2.258081871 | 0.306812765 | 2.428415435 |
| 2.193971001 | 0.316001191 | 2.42675603  |
| 2.233860131 | 0.31567307  | 2.50629162  |
| 2.362649261 | 0.405562368 | 2.592227083 |
| 2.294738392 | 0.38908691  | 2.589900396 |
| 2.311727522 | 0.419713017 | 2.617725746 |
| 2.329416652 | 0.353720837 | 2.834294527 |
| 2.326805782 | 0.356082909 | 2.799403525 |
| 2.408094913 | 0.380053735 | 2.715493282 |
| 2.472384043 | 0.379904484 | 2.804980936 |
| 2.492673173 | 0.380152035 | 2.852720914 |
| 2.606462303 | 0.364216929 | 3.000016196 |
| 2.671751434 | 0.383642347 | 3.143797323 |

|             |             |             |
|-------------|-------------|-------------|
| 2.743640564 | 0.347698652 | 3.19289527  |
| 2.554129694 | 0.387043845 | 2.969548042 |
| 2.645018824 | 0.397362186 | 2.941707245 |
| 2.628607955 | 0.378854646 | 3.079984521 |
| 2.640197085 | 0.361749661 | 3.016355068 |
| 2.539686215 | 0.429397552 | 2.957292099 |
| 2.541975345 | 0.420511074 | 2.850959932 |
| 2.714164476 | 0.436785966 | 2.811183298 |











n et al 2024 (see summary tab).  
 ta products are used to estimate the sink in conjunction with the GOBMs.

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 , 2020.

|         | 2 | 3           | 4        | 5     | 6       | 7         | 8        |
|---------|---|-------------|----------|-------|---------|-----------|----------|
| JMA-MLR |   | LDEO-HPD    | VLIZ-SOM | NIES- | OceanSC | Jena-MLS  | CSIR-ML6 |
|         |   | 1.102975815 |          |       |         | 0.6772095 |          |
|         |   | 1.105233526 |          |       |         | 0.7578295 |          |
|         |   | 1.024491035 |          |       |         | 0.5587139 |          |
|         |   | 1.051491884 |          |       |         | 0.6233977 |          |
|         |   | 1.316824735 |          |       |         | 0.8620396 |          |
|         |   | 1.439915864 |          |       |         | 0.919434  |          |
|         |   | 1.504523787 |          |       |         | 1.012942  |          |
|         |   | 1.413104604 |          |       |         | 0.9133525 |          |
|         |   | 1.247585962 |          |       |         | 0.7363462 |          |
|         |   | 1.40667768  |          |       |         | 0.8550335 |          |
|         |   | 1.505320371 |          |       |         | 1.0051094 |          |

|             |             |         |      |        |           |            |
|-------------|-------------|---------|------|--------|-----------|------------|
|             | 1.346517634 |         |      |        | 0.9551649 |            |
|             | 1.403328027 |         |      |        | 0.9039142 |            |
|             | 1.669554684 |         |      |        | 1.189478  |            |
|             | 1.62317428  |         |      |        | 1.1218663 |            |
|             | 1.509302567 |         |      |        | 1.0573106 |            |
|             | 1.460029955 |         |      |        | 0.9657691 |            |
|             | 1.619670439 |         |      |        | 1.1383437 |            |
|             | 1.769319134 |         |      |        | 1.3813196 |            |
|             | 1.726460952 |         |      |        | 1.3693013 |            |
|             | 1.801225997 |         |      |        | 1.4556431 |            |
|             | 2.146613406 |         |      |        | 1.7505038 |            |
|             | 2.059360414 |         |      |        | 1.5964173 |            |
|             | 2.356802005 |         |      |        | 1.8437201 |            |
|             | 2.551054347 |         |      |        | 2.0092083 |            |
|             | 2.516311602 |         |      |        | 1.8123156 |            |
|             | 2.456637715 |         |      |        | 1.8138298 |            |
|             | 2.530395537 |         |      |        | 2.000543  |            |
|             | 2.459052668 |         |      |        | 2.0439064 |            |
|             | 2.151272869 |         |      |        | 1.7783088 |            |
|             | 2.431488112 |         |      |        | 1.6499037 |            |
| 3.089945718 | 2.447780402 | 2.27573 | 2.27 | 2.2128 | 1.7385264 | 1.7972763  |
| 3.079310739 | 2.860011527 | 2.30934 | 2.36 | 2.2656 | 2.1187421 | 1.96535649 |
| 2.950946226 | 3.158164971 | 2.38808 | 2.3  | 2.3256 | 2.5037371 | 2.00513814 |
| 2.836666826 | 2.944623605 | 2.4568  | 2.26 | 2.3804 | 2.2110625 | 1.92492074 |
| 2.736947312 | 2.191883116 | 2.36864 | 2.25 | 2.3199 | 1.8515432 | 1.95044498 |
| 2.808491155 | 2.080844709 | 2.18035 | 2.27 | 2.3246 | 1.8860407 | 1.91918226 |
| 2.742901935 | 2.035349656 | 2.11061 | 2.31 | 2.3427 | 1.9119511 | 1.93080099 |
| 2.778371278 | 2.384026623 | 2.29732 | 2.33 | 2.4523 | 2.2784572 | 2.03194636 |
| 2.849589332 | 2.357653084 | 2.13863 | 2.5  | 2.4569 | 2.6699735 | 1.98275578 |
| 2.715239042 | 1.896562285 | 1.90334 | 2.45 | 2.2908 | 2.2437688 | 1.91597554 |
| 2.522982244 | 1.921612393 | 1.92991 | 2.36 | 2.311  | 2.0439444 | 2.01059058 |
| 2.436068742 | 1.684074462 | 1.92427 | 2.26 | 2.2506 | 1.5076561 | 1.97560902 |
| 2.625989689 | 2.271550407 | 2.21017 | 2.48 | 2.4464 | 2.5255656 | 2.2832118  |
| 2.866289808 | 2.408207309 | 2.34135 | 2.55 | 2.4673 | 2.8119716 | 2.38371682 |
| 2.778180275 | 2.398756521 | 2.40423 | 2.52 | 2.4451 | 2.7248663 | 2.50223705 |
| 2.813821707 | 2.434407988 | 2.54606 | 2.55 | 2.5199 | 2.4044532 | 2.62107799 |
| 2.906179432 | 2.522197297 | 2.70972 | 2.67 | 2.62   | 2.5527746 | 2.7196533  |
| 2.831954602 | 2.282880139 | 2.75598 | 2.63 | 2.6007 | 2.3374896 | 2.73059352 |
| 2.741797759 | 2.522467616 | 2.78698 | 2.61 | 2.5731 | 2.4145593 | 2.81322073 |
| 2.86906207  | 3.022161095 | 3.07297 | 2.65 | 2.7589 | 2.922963  | 3.04027342 |
| 2.866873621 | 2.975812162 | 2.91744 | 2.56 | 2.7588 | 2.8636476 | 2.9249828  |
| 2.77521705  | 2.971209433 | 2.93562 | 2.55 | 2.6842 | 2.8644351 | 3.10354075 |
| 2.827491476 | 2.806991471 | 3.06231 | 2.62 | 2.7618 | 2.8254787 | 3.16551442 |
| 2.958363477 | 2.784524477 | 3.0718  | 2.76 | 2.75   | 2.9204992 | 3.34736528 |
| 3.042935922 | 3.110520999 | 3.08249 | 2.73 | 2.8113 | 3.1875309 | 3.52999434 |
| 3.221676155 | 2.957056509 | 3.16441 | 2.87 | 2.9267 | 2.9247328 | 3.50886675 |

|             |             |         |      |        |           |            |
|-------------|-------------|---------|------|--------|-----------|------------|
| 3.473886633 | 3.256539794 | 3.17649 | 3.15 | 2.9371 | 3.3987409 | 3.64208868 |
| 3.387925857 | 2.849516666 | 3.14979 | 3.01 | 2.8504 | 3.2151412 | 3.4259878  |
| 3.426940991 | 3.081654918 | 3.17763 | 3.02 | 2.9058 | 3.3924846 | 3.61085388 |
| 3.599246128 | 2.991501358 | 3.0375  | 3.04 | 2.9932 | 3.3806149 | 3.74474564 |
| 3.736386194 | 2.912297083 | 2.84766 | 2.94 | 2.9572 | 3.1479243 | 3.73022356 |
| 3.660992219 | 2.667382771 | 2.68298 | 2.81 | 2.9149 | 2.9819826 | 3.80323955 |
| 3.450510277 | 2.376838658 | 2.38188 | 2.77 | 2.7878 | 2.7421776 | 3.86699399 |
| 3.607509637 | 2.345491633 | 2.50283 | 3.07 | 2.9805 | 3.0414161 | 4.01516163 |











id-10-2567-2017, 2017.

**Average fCO2-products (excl. UExp-FFN-U)**

|           |             |
|-----------|-------------|
| 2.7702347 | 2.770234728 |
| 2.8431536 | 2.84315362  |
| 2.8498427 | 2.849842691 |
| 2.6448053 | 2.644805336 |
| 2.6091285 | 2.609128499 |
| 2.5710612 | 2.571061158 |
| 2.5200439 | 2.520043874 |
| 2.6401047 | 2.640104675 |
| 2.6428743 | 2.642874265 |
| 2.3545708 | 2.35457077  |
| 2.3693632 | 2.369363213 |
| 2.3480535 | 2.348053479 |
| 2.5677037 | 2.567703748 |
| 2.7233755 | 2.723375463 |
| 2.7542564 | 2.754256392 |
| 2.9448463 | 2.944846296 |
| 3.1047732 | 3.104773188 |
| 3.1126682 | 3.11266818  |
| 3.1184782 | 3.118478203 |
| 3.4264406 | 3.42644062  |
| 3.477075  | 3.477075005 |
| 3.5561306 | 3.556130552 |
| 3.6043574 | 3.604357386 |
| 3.6202599 | 3.620259905 |
| 3.6496235 | 3.649623537 |
| 3.7558328 | 3.755832815 |

3.8503744  
3.8840405  
3.9943096  
3.9788698  
4.0295555  
3.9906363  
4.0399229  
4.1507074

3.850374365  
3.884040499  
3.994309568  
3.97886982  
4.029555464  
3.990636253  
4.039922857  
4.150707388









2.217700621  
2.37423319  
2.462862554  
2.398901871  
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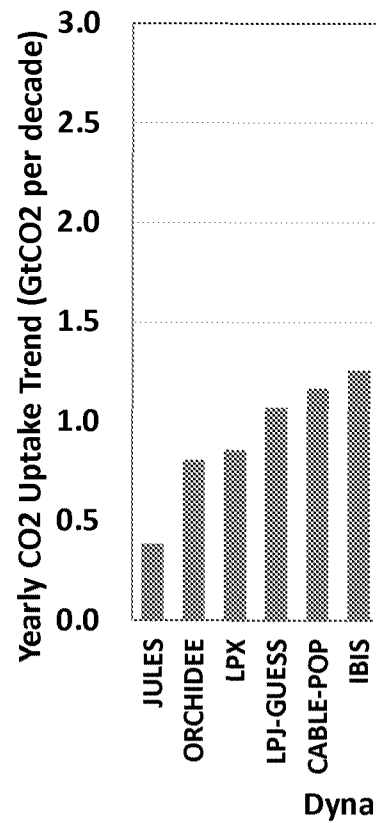
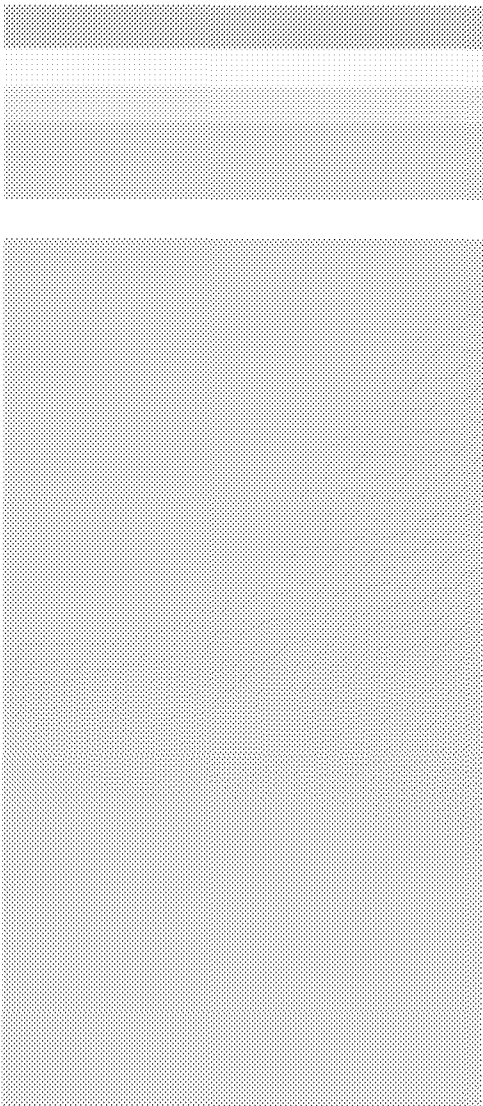








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| 0.9834765 | 0.2684161 | MRI-ESM2-2 |
| 1.0157143 | 0.2772146 | NEMO3.6-P  |
| 1.0212455 | 0.2787242 | MPIOM-HAM  |
| 1.0951148 | 0.2988851 | NEMO-PISC  |
| 1.1102641 | 0.3030197 | MICOM-HAM  |
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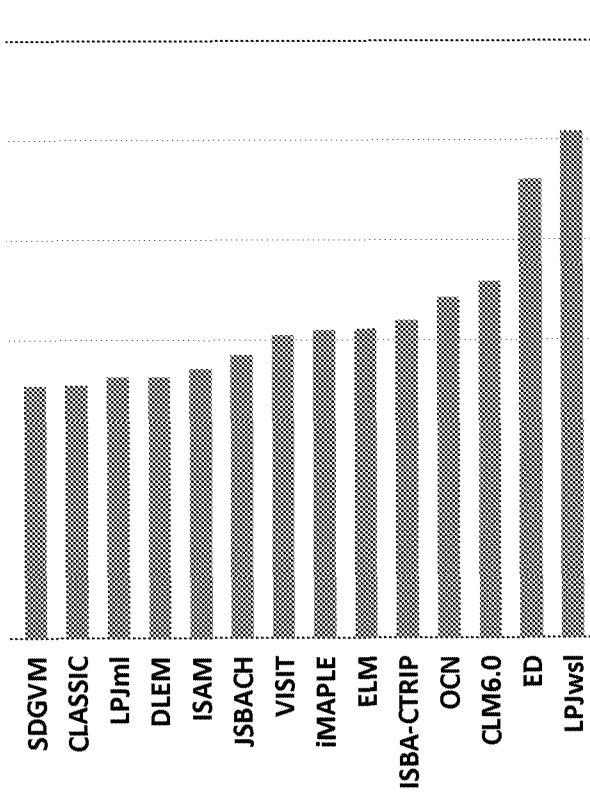




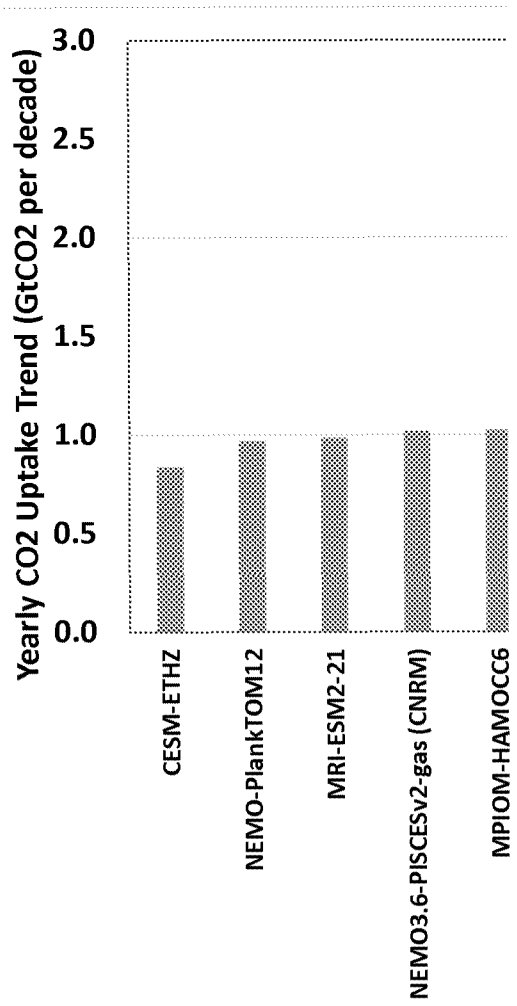








Global Vegetation Model



Global Ocean Biogeochemistry Model

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 kTOM12  
 21  
 ISCESv2-gas (CNRM)  
 MOCC6  
 CES (IPSL)  
 MOCC (NorESM1-OCv1.2)  
 ALT (Princeton)  
 REcoM3  
 SIRO)



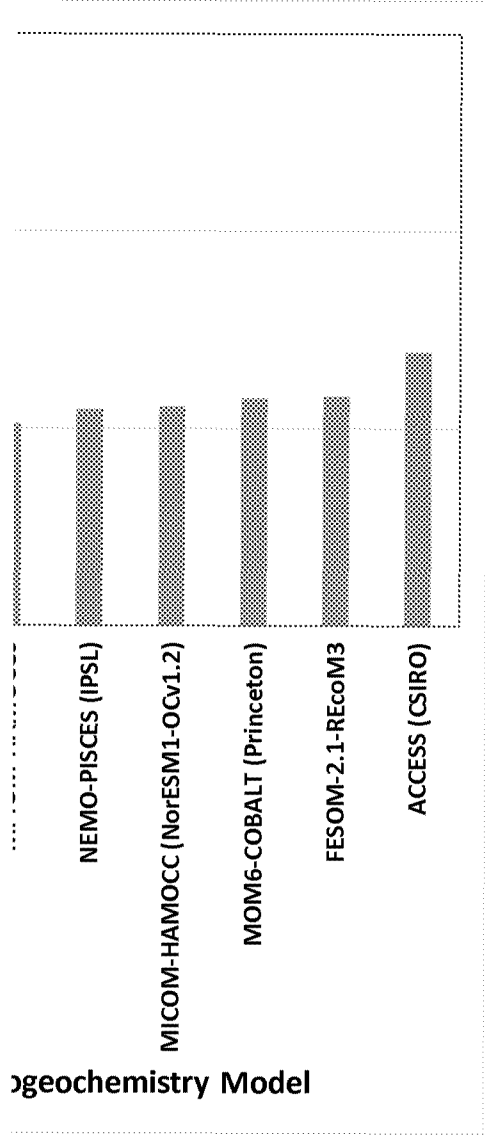














---

**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/18/2025 6:33:18 PM  
**To:** Roy Spencer [roywspencer@hotmail.com]  
**CC:** Judith Curry [curry.judith@gmail.com]; John Christy [climateman60@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Steven Koonin [steven.koonin@gmail.com]  
**Subject:** Re: Ch 13 -vehicles

Roy, that is the intended message but feel free to tweak the wording if needed .

On Sun, May 18, 2025 at 2:31 PM Roy Spencer <roywspencer@hotmail.com> wrote:

Fine, as long as the sequence of causation is not obscured:

- 1) emissions
- 2) carbon cycle removal
- 3) climate system response

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Judith Curry <curry.judith@gmail.com>

Date: 5/18/25 1:27 PM (GMT-06:00)

To: Ross McKittrick <ross.mckittrick@gmail.com>

Cc: "Roy W. Spencer" <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>, Steven Koonin <steven.koonin@gmail.com>

Subject: Re: Ch 13 -vehicles

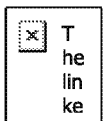
this works, totally agree with moving this material out of Ch 4

On Sun, May 18, 2025 at 11:24 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Travis suggested moving a section from Ch 4 which deals with the planetary scale of the carbon cycle, to a later chapter. I think it would go well in the final chapter with the discussion of motor vehicles. I have merged the material in the attached. Let me know how it looks.

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Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>



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**Sent:** Sunday, May 18, 2025 2:28 PM  
**To:** Ross McKittrick  
**Cc:** Roy W. Spencer; John Christy; Travis Fisher; Steven Koonin  
**Subject:** Re: Ch 13 -vehicles

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**Sent:** 5/18/2025 6:24:32 PM  
**To:** Judith Curry [curry.judith@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climatemanager60@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Steven Koonin [steven.koonin@gmail.com]  
**Subject:** Ch 13 -vehicles  
**Attachments:** 13 U.S.Policy and Global Climate.May18.docx

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## 13 U.S. Climate Policy and the Global Climate

### 13.1 The scale problem

Public policy can only change the rate of emissions, not the concentration in the atmosphere. For criteria air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small - when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO<sub>2</sub> concentration behaves/operates on a very different scale, since the effect we are considering is at the global level and the global carbon cycle is vast and slow. A change in local emissions today will have only a very small global effect, and only with a long delay.

After a pulse (release) of CO<sub>2</sub> emissions to the atmosphere only about 40 percent ( $\pm 15\%$ ) of the extra CO<sub>2</sub> will have been sequestered after twenty years. After a thousand years about 75 percent ( $\pm 10\%$ ) will have been sequestered, and the remainder will be gradually removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently, it will take decades or centuries for U.S. CO<sub>2</sub> emission reductions to have a meaningful impact on the global CO<sub>2</sub> concentration.

To reduce the atmospheric stock of CO<sub>2</sub>, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO<sub>2</sub>. The 1997 Kyoto Protocol proposed to cap industrial nations' CO<sub>2</sub> emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up being too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO<sub>2</sub> levels. It would only have slightly slowed CO<sub>2</sub> growth, reaching the projected year 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, even drastic local actions have minimal local effects, and only with a long delay. The practice of referring to unilateral US reductions as "combatting climate change" or "taking action on climate" reflects a profound misunderstanding of the scale of the issue.

### 13.2 Case study: US motor vehicle emissions

The scale problem can be vividly illustrated with reference to U.S. motor vehicles. The EPA's 2009 Endangerment Finding focused on CO<sub>2</sub> emissions from cars and light-duty trucks in the U.S. because Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. Thus, the 2009 Endangerment Finding obligated the EPA to regulate emissions from new motor vehicles, ostensibly to reduce or eliminate climate-related harms to the US public.

Two questions that naturally arise are: (1) How large a reduction in CO<sub>2</sub> emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed by comparing US vehicle-based CO<sub>2</sub> emissions to the global total. The second question can be addressed by using the fact that the reduction in global warming would be, according to the models relied upon by the EPA, proportional to how much global emissions are reduced, keeping in mind that the change in the CO<sub>2</sub> content of the atmosphere in any given year is the result of total global CO<sub>2</sub> emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.05 billion metric tons of carbon dioxide (GtCO<sub>2</sub>, EPA 2024). Meanwhile global CO<sub>2</sub> emissions from energy use totaled 34.6 GtCO<sub>2</sub> (Energy Institute 2024). Hence U.S. cars and light trucks account for only 3.0% of global energy-related CO<sub>2</sub> emissions. To a first approximation we can say that even eliminating all US vehicle-based emissions would change the multidecadal warming trend by at most 3%. If we were to take into account emissions from land use and cement production, that fraction would be even smaller, but for the purpose of the following calculation, it will suffice.

For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends from five global temperature datasets range from +0.163 deg. C per decade in the NCEP/NCAR R1 reanalysis dataset to +0.211 deg. C per decade in the ERA5 reanalysis dataset. We can take this to be the range of precision with which we can estimate global warming. The latter estimate is 29% larger than the former, indicating that reduction in the rate of global warming from eliminating U.S. vehicle CO<sub>2</sub> emissions would be an order of magnitude below the limits of measurability. Likewise if vehicle emissions were reduced by only, say, 10 percent, the effect on the climate would be two orders of magnitude below the limits of measurement.

Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO<sub>2</sub> emissions would be even less measurable.

Consequently, due to the nature of the CO<sub>2</sub> issue, and in contrast to the case of local air contaminants like particulates and ozone, even aggressive regulatory actions on GHGs cannot be expected to remediate alleged climate dangers to the US public on any even remotely-measurable scale.

EPA (2024) *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions 1990-2022*. Available online at <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P101AKR0.pdf>

Energy Institute (2024) *Statistical Review of World Energy*. Available online at <https://www.energyinst.org/statistical-review>

---

**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Thursday, May 15, 2025 5:53 PM  
**To:** Travis Fisher  
**Cc:** Steven Koonin; Judith Curry; John Christy; Roy W. Spencer  
**Subject:** Re: Part I

This link should give you edit access to the whole folder. The files you want are in 01.Report Draft

[https://www.dropbox.com/scl/fo/wahx6lpwzu33m5vyrr8x/ANTU1qAQJ-zXCFzP\\_gsJcOs?rlkey=fe667xxscc7wk2dlstcwyywg4&st=qdj1orfv&dl=0](https://www.dropbox.com/scl/fo/wahx6lpwzu33m5vyrr8x/ANTU1qAQJ-zXCFzP_gsJcOs?rlkey=fe667xxscc7wk2dlstcwyywg4&st=qdj1orfv&dl=0)

On Thu, May 15, 2025 at 5:41 PM Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:  
I know someone in that department! Do I need any additional authorities / rights in Dropbox to edit the documents directly?

On Thu, May 15, 2025 at 3:29 PM Ross McKittrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:  
I did the merger and renumbered the sections and figures in ch's 2 and 3. In the 01.Report Draft folder the chapters now go 1, 2, 4, 5,... so perhaps someone from the DoE Department of Report Chapter Renumbering could go through and adjust Ch4 to Ch3, 5 to 4, etc., taking care to renumber the figures and the references in each chapter to other chapters as necessary.

On Thu, May 15, 2025 at 3:09 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Yes, we should combine as Judy suggests.

SEK

PS There is already a separate thread on the coral issue.

---

**From:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>  
**Sent:** Thursday, May 15, 2025 8:30 AM  
**To:** Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>  
**Cc:** Ross McKittrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** Part I

Another thought I had last night (instead of sleeping)

I suggest combining chapters 2 and 3 into one chapter:

## 2. Direct environmental impacts of CO2

### 2.1 Land - global greening

### 2.2 Ocean - alkalinity

In the alkalinity chapter, I think we should remove discussion of coral reefs, since that is mostly a temperature issue

On Wed, May 14, 2025 at 4:18 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

That works. Thanks.

SEK

**From:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>

**Sent:** Wednesday, May 14, 2025 7:17 PM

**To:** Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>

**Cc:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>; John Christy <[climatemanager60@gmail.com](mailto:climatemanager60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

**Subject:** Re: New folder: 01.Report Draft

This should get you in

[https://www.dropbox.com/scl/fo/wahx6lpwzu33m5vyrr8x/ANTU1qAQJ-zXCFzP\\_gsJcOs?rlkey=l1z3qj9v46e1t5f4ywwxq7p8c&dl=0](https://www.dropbox.com/scl/fo/wahx6lpwzu33m5vyrr8x/ANTU1qAQJ-zXCFzP_gsJcOs?rlkey=l1z3qj9v46e1t5f4ywwxq7p8c&dl=0)

This is for the parent folder. Let me know if it doesn't work.



On Wed, May 14, 2025 at 6:41 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Can you please send a link to the new folder?

Thanks.

Steven E. Koonin

> On May 14, 2025, at 15:27, Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

>

>

> Following our meeting today I created a new folder containing clean copies (all past tracked changes accepted) of all chapters.

> There are some marginal queries and in-line comments remaining to be resolved, missing Figure captions in a couple of places etc. If you are able to supply the missing info go ahead and do so. We will soon need to sign off on final text versions so please read through them.

> I propose that these should be the versions we talk through next week.

>

> Question: should there be a single list of references at the very end or should each chapter have its own reference list? Initially I thought the former but now I lean towards the latter.

>

---

**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Thursday, May 15, 2025 5:41 PM  
**To:** Ross McKitrick  
**Cc:** Steven Koonin; Judith Curry; John Christy; Roy W. Spencer  
**Subject:** Re: Part I

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**Cc:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

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**Sent:** Thursday, May 15, 2025 3:29 PM  
**To:** Steven Koonin  
**Cc:** Judith Curry; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Re: Part I

I did the merger and renumbered the sections and figures in ch's 2 and 3. In the 01.Report Draft folder the chapters now go 1, 2, 4, 5,... so perhaps someone from the DoE Department of Report Chapter Renumbering could go through and adjust Ch4 to Ch3, 5 to 4, etc., taking care to renumber the figures and the references in each chapter to other chapters as necessary.

On Thu, May 15, 2025 at 3:09 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Yes, we should combine as Judy suggests.

SEK

PS There is already a separate thread on the coral issue.

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**Sent:** Thursday, May 15, 2025 10:45 AM  
**To:** 'Judith Curry'; 'Ross McKittrick'  
**Cc:** 'John Christy'; 'Roy W. Spencer'; 'Travis Fisher'  
**Subject:** RE: Part I

We will have to say SOMETHING about coral, whether in the report or in response to criticisms about leaving it out. I'd prefer the former.

SEK

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**Sent:** Thursday, May 15, 2025 10:34 AM  
**To:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Cc:** Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
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**Subject:** Re: Part I

Is this an area where you could assign some research work to me and Josh? For my part, I don't mind the extra effort, and I think retaining some negative trends (even if the systems are complex or not well understood) will cut against accusations of bias.

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On Wed, May 14, 2025 at 4:18 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

That works. Thanks.

SEK

---

**From:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>  
**Sent:** Wednesday, May 14, 2025 7:17 PM  
**To:** Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>  
**Cc:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>; John Christy <[climatemanager60@gmail.com](mailto:climatemanager60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** Re: New folder: 01.Report Draft

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This is for the parent folder. Let me know if it doesn't work.

On Wed, May 14, 2025 at 6:41 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Can you please send a link to the new folder?

Thanks.  
Steven E. Koonin

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>  
> Question: should there be a single list of references at the very end or should each chapter have its own reference list? Initially I thought the former but now I lean towards the latter.  
>

---

**From:** Judith Curry [curry.judith@cfanclimate.com]  
**Sent:** 5/15/2025 2:12:50 PM  
**To:** Steven Koonin [steven.koonin@gmail.com]  
**CC:** Ross McKittrick [ross.mckittrick@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: Part I  
**Attachments:** (17) Grok : X.pdf

I did a Grok3 search on coral reef health (attached). If we are going to discuss coral reefs, we have to do a lot more than reference Peter Ridd. I suggest we leave this out.

On Thu, May 15, 2025 at 5:47 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Climate-driven loss of coral is certainly out there in the public consciousness. So we need to say We need to say something somewhere about it lest we be criticized for avoiding discussion of it - ie cherry picking the impacts we cover.

Steven E. Koonin

On May 15, 2025, at 05:29, Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)> wrote:

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**Subject:** Re: New folder: 01.Report Draft

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[https://www.dropbox.com/sc/fo/wahx6lpwzu33m5vyri8x/ANTU1qAQJ-zXCFzP\\_gsJcOs?rlkey=llz3qj9v46e1t5f4ywwxq7p8c&dl=0](https://www.dropbox.com/sc/fo/wahx6lpwzu33m5vyri8x/ANTU1qAQJ-zXCFzP_gsJcOs?rlkey=llz3qj9v46e1t5f4ywwxq7p8c&dl=0)

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Key Points

- Research suggests coral reefs are declining globally, with over 50% lost since 1957.
- The evidence leans toward climate change as the main cause, causing bleaching and acidification.
- It seems likely local factors like overfishing and pollution also impact reef health significantly.

Overview

Coral reefs are vital ecosystems facing serious challenges. Studies show they are declining, with major impacts from climate change, including warmer oceans and acidification. Local issues like overfishing and pollution add to the stress. Recent events, like the 2022-2024 bleaching, have worsened the situation, affecting over 80% of reefs.

Detailed Findings

- Decline Status:** Research indicates a significant global decline, with a 50% loss in coverage since 1957 and 84% of coral species at risk of extinction by 2034.
- Climate Impact:** Rising ocean temperatures cause bleaching, where corals expel algae, risking death. Acidification from CO2 reduces calcium for coral skeletons, hindering growth.
- Local Factors:** Overfishing disrupts ecosystem balance, pollution degrades water quality, and coastal development adds physical damage, all reducing reef resilience.

For more details, see reports from EPA, UNEP, and NOAA.

Comprehensive Analysis of Coral Reef Health

Coral reefs, often referred to as the "rainforests of the sea," are critical ecosystems supporting a quarter of all marine species and providing essential services like coastal protection and fisheries. However, recent scientific assessments and reports, such as May 15, 2025, paint a concerning picture of their health, with evidence pointing to a global decline driven by both global and local factors. This analysis delves into the current status, causes of decline, and recent developments, drawing from authoritative sources like the Environmental Protection Agency (EPA), United Nations Environment Programme (UNEP), NASA, and the International Union for Conservation of Nature (IUCN).

Current Status of Coral Reefs

Research suggests that coral reefs are experiencing a significant decline. A study published by the Natural History Museum in 2021 found that coral reef coverage has fallen by over 50% since 1957, with associated biodiversity declining by 63% and fish abundance dropping by 60% in the Pacific. The IUCN Red List update from November 2024 further highlighted the severity, noting that 84% of reef-building coral species are now at risk of extinction, up from one-third in 2008. The IUCN Blue List also underscores the urgency, with recent events amplifying the crisis.

A Guardian article from April 2025 reported that more than 90% of the world's coral reefs were hit by bleaching during the worst global event on record, spanning 2023 to 2024, with surveys indicating widespread coral mortality. The Global Coral Reef Monitoring Network (GCRMN) is compiling a 2025 status report, but preliminary data suggest the impact is profound, with recovery uncertain given ongoing stressors.

Regionally, the Great Barrier Reef, one of the largest reef systems, faces compounded pressures. The 2024 Outlook Report noted some ecosystem improvements, like seagrass meadows, due to management efforts, but climate-driven threats like warming oceans and cyclones continue to challenge resilience. Despite record growth in some areas post-bleaching, as noted in a 2023 WHC article, the overall outlook remains dire.

Causes of Variations in Coral Reef Health

The decline in coral reef health is driven by a complex interplay of global and local factors, each contributing to the stress on these ecosystems. Below is a detailed breakdown, organized by category, with supporting evidence from recent studies and reports.

Climate Change: The Dominant Global Threat

Climate change impacts as the primary driver, with ocean warming and acidification at the forefront. Rising sea temperatures cause coral bleaching, a process where corals expel their symbiotic algae (zooxanthellae), their primary food source, leading to starvation and potential death if conditions persist. The UNEP notes that mass bleaching events are predicted to increase in frequency and intensity as temperatures rise, with projections suggesting a 70-90% decline in live coral by 2050 at 1.5°C warming, and nearly 90% at 2°C. The planet has already warmed by 1.1°C since the 19th century, exacerbating the issue.

Ocean acidification, resulting from increased CO2 absorption, reduces the availability of calcium carbonate, essential for coral skeleton formation. The Natural History Museum explains that this process makes seawater more acidic, dissolving coral structures and reducing their ability to rebuild, with some reefs already beginning to dissolve. Natural History Museum, NASA's research, using satellite data, confirms that sea surface temperature and water quality changes are closely linked to coral health declines.

Local Factors: Adding Pressure to Vulnerable Systems

Local human activities significantly contribute to coral reef decline, often compounding the effects of climate change. These factors include:

- Overfishing:** Overfishing disrupts the ecological balance, reducing fish populations that control algae growth. The Natural History Museum study found that catches of coral reef fishes peaked in 2002 and have declined since, despite increased fishing effort, affecting 6 million people dependent on these fisheries. Natural History Museum. This loss impacts diets and livelihoods, particularly in tropical and small-island developing states.
- Pollution:** Pollution, including chemical runoff, fertilizers, and toxins, degrades water quality, stressing corals and making them more susceptible to bleaching. The EPA highlights that most coral reefs occur in shallow waters near shore, making them vulnerable to land-based pollution. EPA. Recent initiatives, like the Trash-Free Waters program in Puerto Rico, aim to reduce wastewater loading by 2025, but challenges remain.
- Unsustainable Coastal Development:** Activities like dredging and construction increase sedimentation, blocking sunlight and smothering corals. The UNEP notes that unsustainable coastal development adds local pressures, reducing reef resilience. UNEP. Physical damage from ships and divers, as mentioned in NASA's analysis, also plays a role.
- Disease:** Climate change and stressors like pollution make corals more susceptible to infectious diseases, which can spread rapidly. A ScienceDaily article from March 2025 highlighted the role of diseases, particularly in the Caribbean, in causing major declines in coral populations, affecting species like staghorn and elkhorn corals. ScienceDaily.

These local factors interact with global climate impacts, creating a feedback loop that reduces coral reefs' ability to recover. For instance, a reef weakened by bleaching may be more vulnerable to disease outbreaks or physical damage from storms.

Recent Developments and Future Outlook

Recent developments underscore the ongoing crisis. The 2023-2024 global bleaching event, driven by record ocean temperatures, has been particularly devastating, with the Guardian reporting widespread coral death following surveys. ScienceDaily articles from early 2025 discuss challenges in coral restoration, noting that over a third of projects fail and may not scale effectively to mitigate losses. ScienceDaily. This suggests that while efforts like those by the Coral Reef Alliance are underway, the scale of the problem remains daunting.

Management initiatives, such as controlling crown-of-thorns starfish and enhancing tiger patrols on the Great Barrier Reef, show promise, but the 2024 Outlook Report emphasizes that climate change compromises recovery capacity. The GCRMN's call for data for the 2025 report indicates ongoing efforts to monitor and understand the extent of damage, but preliminary findings suggest the picture is grim.

Summary of Causes and Impacts

To organize the causes and their impacts, the following table summarizes the key factors and their effects on coral reef health:

| Cause                          | Impact on Coral Reefs                                                           |
|--------------------------------|---------------------------------------------------------------------------------|
| Climate Change (Warming)       | Causes bleaching, increases mortality, reduces recovery potential.              |
| Climate Change (Acidification) | Dissolves coral skeletons, hinders growth, reduces biodiversity.                |
| Overfishing                    | Disrupts ecosystem balance, reduces fish that control algae, affects fisheries. |
| Pollution                      | Degrades water quality, stresses corals, increases disease susceptibility.      |
| Coastal Development            | Increases sedimentation, blocks sunlight, causes physical damage.               |
| Diseases                       | Spreads rapidly, causes mortality, particularly in stressed reefs.              |

This table highlights the multifaceted nature of the threats, with climate change as the overarching driver and local factors amplifying the decline.

Conclusion  
In conclusion, coral reefs are declining globally, with research suggesting over 50% loss since 1957 and recent bleaching events affecting over 80% of reefs. The evidence leans toward climate change, particularly ocean warming and acidification, as the main cause, with local factors like overfishing, pollution, and coastal development adding significant pressures. Addressing this decline requires urgent global action to reduce emissions and local efforts to mitigate human impacts, though the outlook remains challenging given the scale and speed of current changes.

Key Citations

- EPA Threats to Coral Reefs
- UNEP Why are Coral Reefs Dying
- NASA Visualizing Corals Data Tracking
- Natural History Museum Coral Reef Cover Loss
- IUCN Red List Coral Species Extinction
- The Guardian Coral Reef Bleaching Crisis
- WHC Great Barrier Reef Recovery
- USFWS Great Barrier Reef Outlook Report
- ScienceDaily Coral Reefs News Updates
- EPA US Coral Reefs Initiatives
- GCRMN 2025 Report Call for Data
- Coral Reef Alliance State of Reef Report

18 web pages

2 3 4

Ask anything

100% completion 0% time 0% edit image

Justin Curry  
@jcurry

DOJ\_00041581

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Thursday, May 15, 2025 8:48 AM  
**To:** Judith Curry  
**Cc:** Ross McKittrick; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Re: Part I

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Steven E. Koonin

On May 15, 2025, at 05:29, Judith Curry <curry.judith@cfanclimate.com> wrote:

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**Subject:** Re: New folder: 01.Report Draft



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On Wed, May 14, 2025 at 6:41 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Can you please send a link to the new folder?

Thanks.

Steven E. Koonin

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**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Thursday, May 15, 2025 8:30 AM  
**To:** Steven Koonin  
**Cc:** Ross McKittrick; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Part I

Another thought I had last night (instead of sleeping)

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Tuesday, May 20, 2025 3:24 PM  
**To:** Travis Fisher  
**Subject:** Re: Chapters 1, 2 and 4

Go ahead and make those kinds of revisions but underline them or something so we can do a final ok. Please put everything into a common font. The template has font selections. It's a tricky change to make. You have to make sure it doesn't eliminate italics or other formatting

On Tue, May 20, 2025 at 2:02 PM Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:  
Thanks, Ross! Adding them in now.

Did you guys decide on a consistent font to use throughout the report? I can also just leave the multiple fonts as they are, and we can change that last.

Also, for things like the citation to Mass v. EPA, I know for sure the citation should say 2007, but the text in the draft says 2006 (in chapter 1). If I make corrections like those, do you think the team will be ok with that, or do I need to track them and get the team's review?

On Tue, May 20, 2025 at 1:07 PM Ross McKittrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:  
These are ready.  
Cheers,  
ROss

---

**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Tuesday, May 20, 2025 2:03 PM  
**To:** Ross McKitrick  
**Subject:** Re: Chapters 1, 2 and 4

Thanks, Ross! Adding them in now.

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These are ready.

Cheers,

ROss

---

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Wednesday, May 21, 2025 10:03 AM  
**To:** Steven Koonin  
**Cc:** Roy Spencer; Judith Curry; John Christy; Travis Fisher  
**Subject:** Re: carbon cycle revision

That text looks good. This version is now the entry in the post-meeting folder. It also contains Roy's updated scenario figure.

On Wed, May 21, 2025 at 9:10 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

The attached contains my revision of the carbon cycle material, section 3.3.2

As I'm somewhat DropBox challenged, I've not posted it, but hope that Ross can incorporate it into the working draft.

Steve Koonin

---

**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/21/2025 1:10:04 PM  
**To:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Roy Spencer' [roywspencer@hotmail.com]; 'Judith Curry' [curry.judith@gmail.com]; 'John Christy' [climatemanager60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** carbon cycle revision  
**Attachments:** 3.AnthropogenicRF.May19[SEK].docx

The attached contains my revision of the carbon cycle material, section 3.3.2

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Steve Koonin

### 3 Human influences on the climate

#### **Chapter Summary**

*The global climate is naturally variable on all time scales. Anthropogenic CO<sub>2</sub> emissions add to that variability by changing the total radiative balance in the atmosphere.*

*The IPCC has downplayed the role of the sun in climate change but there are plausible solar irradiance reconstructions that imply it contributed to recent warming.*

*Climate projections are based on IPCC emission scenarios that have tended to exceed observed trends. The vast majority of academic climate “impacts” studies in recent years are based upon the extreme RCP8.5 scenario that is now considered implausible; its use as a business-as-usual scenario has been misleading.*

*Carbon cycle models connect annual emissions to growth in the atmospheric CO<sub>2</sub> stock. Models disagree over the rate of land and ocean CO<sub>2</sub> uptake but all agree that it has been increasing since 1959.*

#### 3.1 Components of radiative forcing and their history

##### 3.1.1 Historical radiative forcing

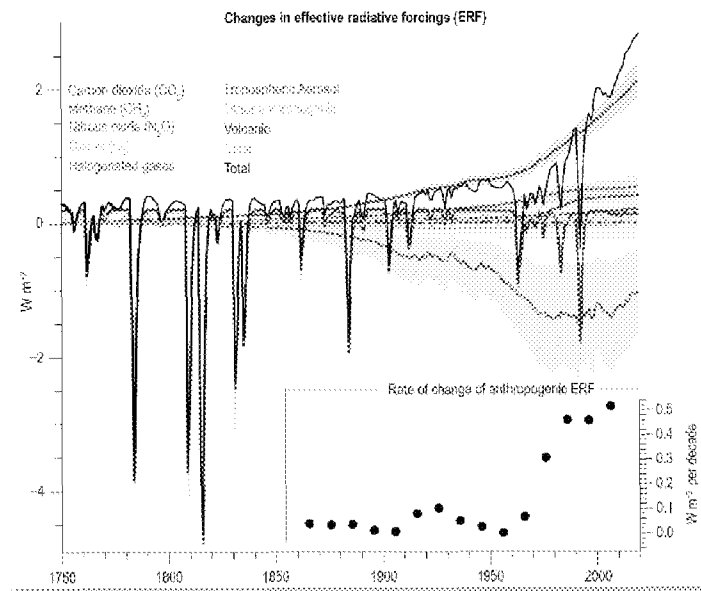
A changing climate has been the norm throughout the Earth’s 4.6-billion-year history. The Earth’s temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by emissions of CO<sub>2</sub> and other greenhouse gases and by altering the concentration of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and is cooled by the radiative heat it emits to space. Averaged over the Earth’s surface, each of these processes involve power flows of about 240 Watts per square meter (W/m<sup>2</sup>). When they are in balance, there are no net external causes of warming or cooling. Both human and natural influences on the climate alter this balance and so cause the climate to change.

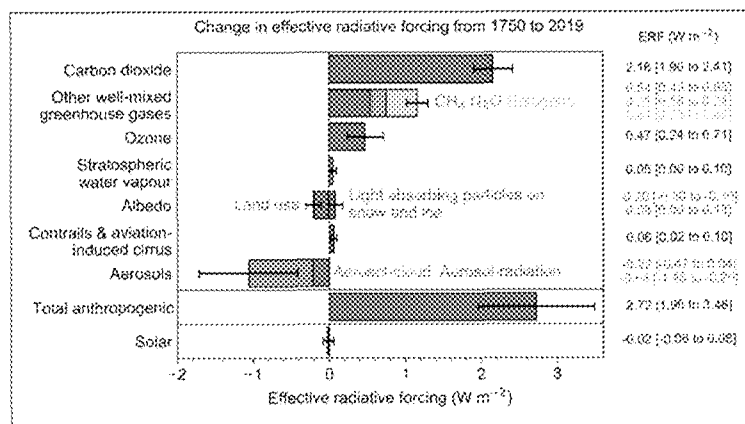
Influences on the Earth’s energy balance at the top of the atmosphere are quantified by “radiative forcing”, the extent to which they disturb the warming/cooling balance; a positive forcing warms



while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from its AR6.



**Figure 3.1.1:** IPCC estimates of radiative forcing components over time. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/>



**Figure 3.1.2** IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/>

These graphs show that the total radiative forcing is comprised of both natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the influence of energy systems. It exerts a warming influence by decreasing the

cooling power of the atmosphere. Emissions of CO<sub>2</sub> are accumulating in the atmosphere, as described in the following section, so that the warming influence is increasing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone) act similarly, currently adding another 75% to CO<sub>2</sub>'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding the causes of recent warming requires not just identifying the warming effects of CO<sub>2</sub>, but also the more uncertain cooling effects of aerosols.

The IPCC views the change in the radiative forcing by the sun to be negligible, based on their preference for reconstructions that imply minimal solar change since preindustrial times. Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature covering the 1600-2000 interval; they vary from almost no change in TSI to a relatively large upward trend. Those authors note that the variation in TSI reconstructions combined with variations in surface temperature reconstructions allows for inferences consistent with either no or most 20<sup>th</sup> Century warming being attributable to the sun.

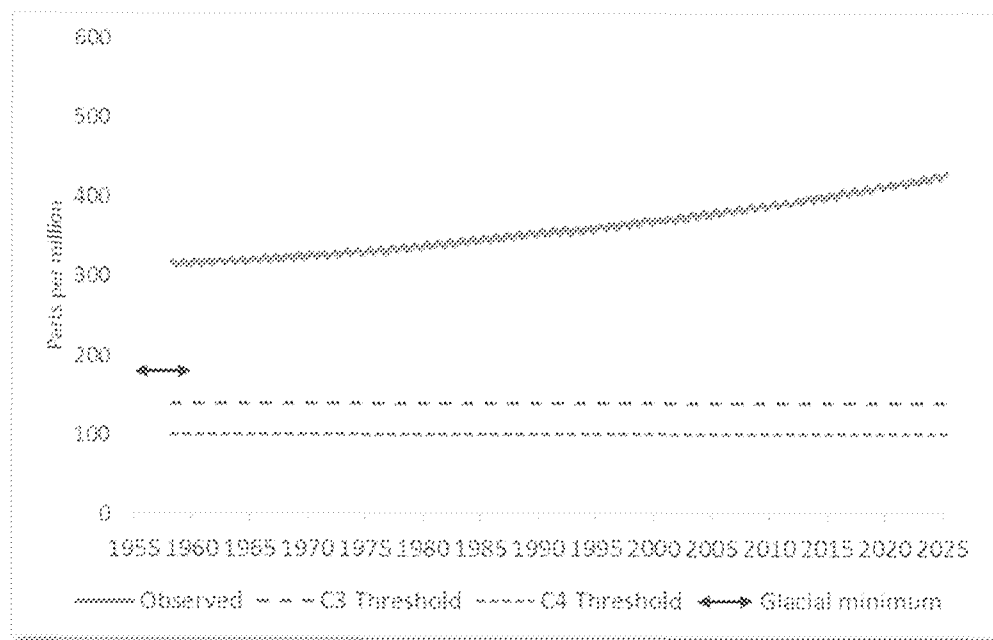
A particularly thorny issue is the gap in TSI data between 1989 and 1991 due to a delay in the launch of a monitor following the Space Shuttle Challenger disaster on January 28 1986. That prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta et al. 2019). This is called the ACRIM (Active Cavity Radiometer Irradiance Monitor) gap problem. The question of whether there is an upward trend in TSI over 1978 to 2018 comes down to how the ACRIM data gap is filled. Connolly et al. (2023) found that the IPCC's consensus statements on solar forcing were prematurely formulated through the suppression of dissenting scientific opinions.

The other natural radiative forcing component is largely volcanic aerosols, which exert an episodic cooling influence. Box 4.1 in the IPCC AR6 Report addresses the climate impact of volcanic eruptions, noting three explosive volcanic eruptions that occurred in the first half of the 19<sup>th</sup> century. This included the 1815 Tambora eruption that resulted in the 'year without summer', with multiple harvest failures across the Northern Hemisphere. There is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins et al. 2023, Schoeberl et al. 2024)

The anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m<sup>2</sup> today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing; state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m<sup>2</sup>. Natural sources of global energy imbalance other than volcanoes and total solar irradiance (TSI) are not included in these graphs because they remain largely unknown.

### 3.1.2 Change in atmospheric CO<sub>2</sub> since 1958

Carbon dioxide's warming influence depends upon how much "extra" CO<sub>2</sub> accumulates in the atmosphere- *i.e.*, its concentration above the preindustrial value of 280 ppm. The CO<sub>2</sub> level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are available online at <https://gml.noaa.gov/ccgg/trends/index.html>. The concentration was about 316 ppm at the start of the record in 1959 and is now about 430 ppm, a 36 percent increase. At the end of the last glaciation CO<sub>2</sub> levels had fallen to about 180 ppm. As discussed in Chapter 2 C3 plants begin dying at CO<sub>2</sub> levels below about 140 ppm and C4 plants at CO<sub>2</sub> levels below 100 ppm, so if CO<sub>2</sub> levels had continued falling plant life might have been in peril.



**Fig. 3.1.3.** CO<sub>2</sub>: Yearly average atmospheric CO<sub>2</sub> concentrations (1959-2025) in ppm measured at Mauna Loa (blue). C3 Threshold: Level below which C3 plants begin dying (140 ppm, see Chapter 2). C4 Threshold: Level below which C4 plants begin dying (100 ppm, see Chapter 2). Glacial minimum: Minimum level during recent glaciations (purple arrow). CO<sub>2</sub> data source: <https://gml.noaa.gov/ccgg/trends/index.html>

The annual increase in concentration is only about half of the CO<sub>2</sub> emitted because land and ocean processes currently absorb “excess” CO<sub>2</sub> at a rate approximately 50% of the human emissions. Future concentrations, and hence future human influences on the climate, therefore depend upon two components: (1) future rates of global human CO<sub>2</sub> emissions, and (2) how fast the land and ocean remove extra CO<sub>2</sub> from the atmosphere. We discuss each of these in turn.

### 3.2 Urbanization influence on temperature trends

Historical temperature data over land has been collected mainly where people live. This raises the problem of how to filter out non-climatic warming signals due to Urban Heat Islands (UHI) and other changes to the land surface. If they are not removed the data may over-attribute observed warming to greenhouse gases. The IPCC acknowledges that raw temperature data are contaminated with UHI effects but claims to have data cleaning procedures that remove them. It is an open question whether those procedures suffice for the purpose.

AR6 downplayed the issue by saying (WGI p. 235) that no recent evidence had emerged to alter the AR5 finding that urbanization causes an upward bias of no more than 10% in the global land surface warming trend. AR5 (WGI p. 189) also cited the 10% upper bound without citing a source. AR4 (WGI p. 244) cited Jones et al. (1990) and Peterson et al. (1999) as the basis of the claim. Peterson et al. had failed to find any difference in trends between rural and urban samples, although their definition of rural included local populations up to 10,000 persons and the relative influence of urbanization begins well below that (Spencer et al 2025). Jones et al. compared rural/urban warming in three regions: Eastern Australia, Eastern China and Western Soviet Union. Their definition of “rural” included towns of up to 10,000 in the former Soviet Union and up to 100,000 in China. They found relative warming biases greater than 10% in these areas but conjectured that the urbanization effect averaged over the areas they did not examine would bring the global land bias to under 10% of the observed warming trend.

Prior to the IPCC AR4 several papers appeared in print arguing that the warming effect of UHIs added a relatively large (30-50%) component to observed warming and was not simulated by climate models (de Laat and Maurellis 2006, McKittrick and Michaels 2007). These findings were based on correlations between locations of maximum warming over land with locations of maximum socioeconomic development. AR4 asserted (p. 244) that these correlations were an artefact of natural atmospheric circulations and were in fact statistically insignificant, and on that basis set the findings aside. The claim attracted controversy because it was presented with no supporting evidence. McKittrick (2010) and McKittrick and Nierenberg (2010) showed that taking into account various conjectured alternative explanations for the correlations did not affect their significance. The AR5 (p. 189) conceded that the AR4 had provided “no explicit

evidence” for its assessment and further acknowledged, based on these papers, that there was “significant evidence for such contamination of the record” i.e. a warming bias in the land record. However as noted, elsewhere in the report they carried forward the AR4 claim that it was less than 10% of observed warming and they expressed no caution against using the land record for climate measurement on the assumption that it is not contaminated with UHI bias. Recently Soon et al. (2023) estimated an urbanization bias in the Northern Hemisphere land record over 1850-2018 sufficient to increase the trend in the blended record from 0.55°C to 0.89°C per century.

Some studies providing evidence against UHI contamination compared warming rates between rural and urban locations (Jones et al. 1990, Peterson et al. 1999, Wickham et al. 2013). It is not known whether such methods would be capable of detecting UHI bias even when present. The influence of UHI warming is logarithmic, in other words it is strongest at low population growth levels then tapers off as local urbanization expands (Oke 1973, Spencer et al. 2025). Hence finding the same or more warming in rural areas than in nearby urban areas is consistent either with UHI bias being absent or present. McKittrick (2013) provided an empirical demonstration in which the rural/urban trends were not significantly different in a data set shown on other grounds to be contaminated with UHI bias.

Parker (2006) instead examined a sample of urban locations and found no difference in trends between subsets partitioned according to nighttime wind speed, concluding on this basis that urbanization could not be a significant factor. Here again the question is whether such a method would find UHI bias even if present. McKittrick (2013) presented an example in which UHI-contaminated data did not exhibit significant trend differences when stratified according to wind speed.

The challenge in measuring UHI bias is relating local temperature change to a corresponding change in population or urbanization, rather than to a static classification variable such as rural or urban. Spencer et al. (2025) use newly-available historical population archives to undertake such an analyses and found evidence of significant UHI bias in US summertime temperature data.

In summary while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanization and that these biases are not removed by the data processing algorithms used to produce climate data sets.

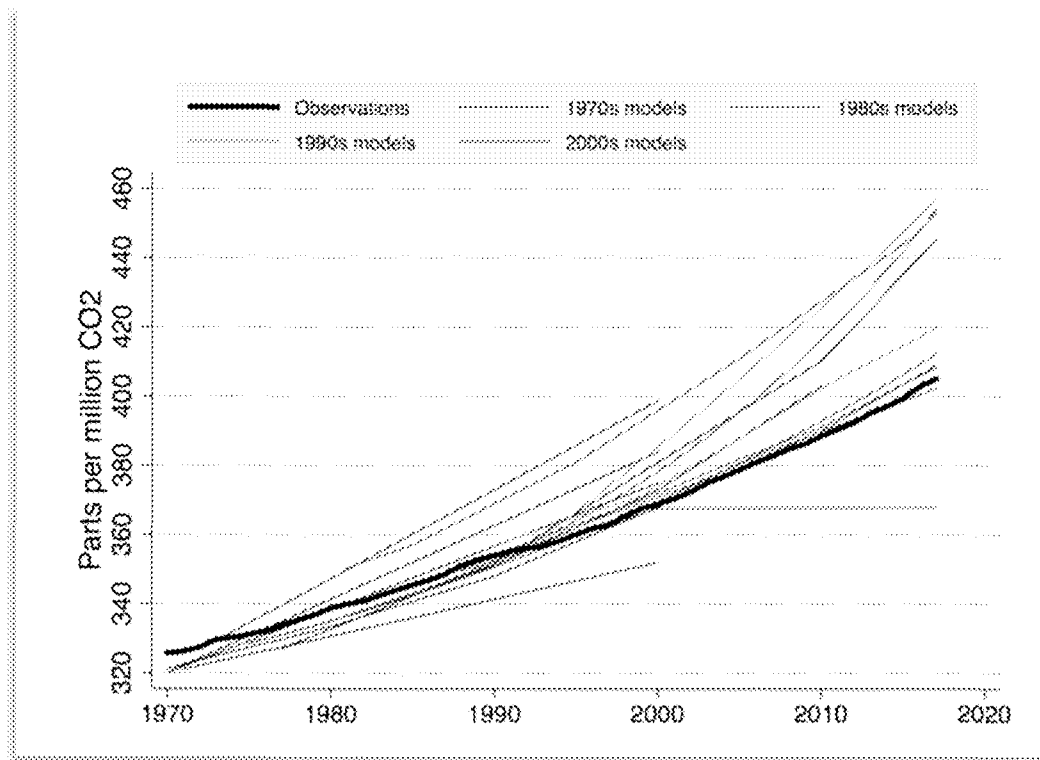
### 3.3 Future emission scenarios and the carbon cycle

#### 3.3.1 Emission scenarios

Because of the great uncertainties about these many factors in the decades to come, Assessing the dangers of future GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic activity, regulation, and energy and agricultural technologies. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, and technologies. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m<sup>2</sup> of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m<sup>2</sup>.)

Although the IPCC does not claim its emission scenarios are forecasts, they are often treated as such. Comparisons of past scenario groups against observations show a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* was used; these were referred to as the SREP scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita values, the SREP scenario emissions distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO<sub>2</sub> emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis of Hausfather *et al.* (2019) who showed that observed atmospheric CO<sub>2</sub> concentrations tracked the low end of the SRES range and also of subsequent IPCC scenario ranges.



**Figure 3.3.1** Comparison of observed atmospheric CO<sub>2</sub> levels (black line) with scenario projections (colored lines, mainly IPCC) since the 1970s. Source: Hausfather et al. (2019) Figure S4.

For AR5 the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCPs). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying an anthropogenic radiative forcing in 2100 of 2.6 W/m<sup>2</sup>) projects a GHG concentration pathway leading to warming well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21<sup>st</sup> century world in the absence of increasingly stringent emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its use as a business-as-usual baseline has been criticized as grossly misleading.<sup>1</sup> Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was

<sup>1</sup> This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future.

developed as an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting.

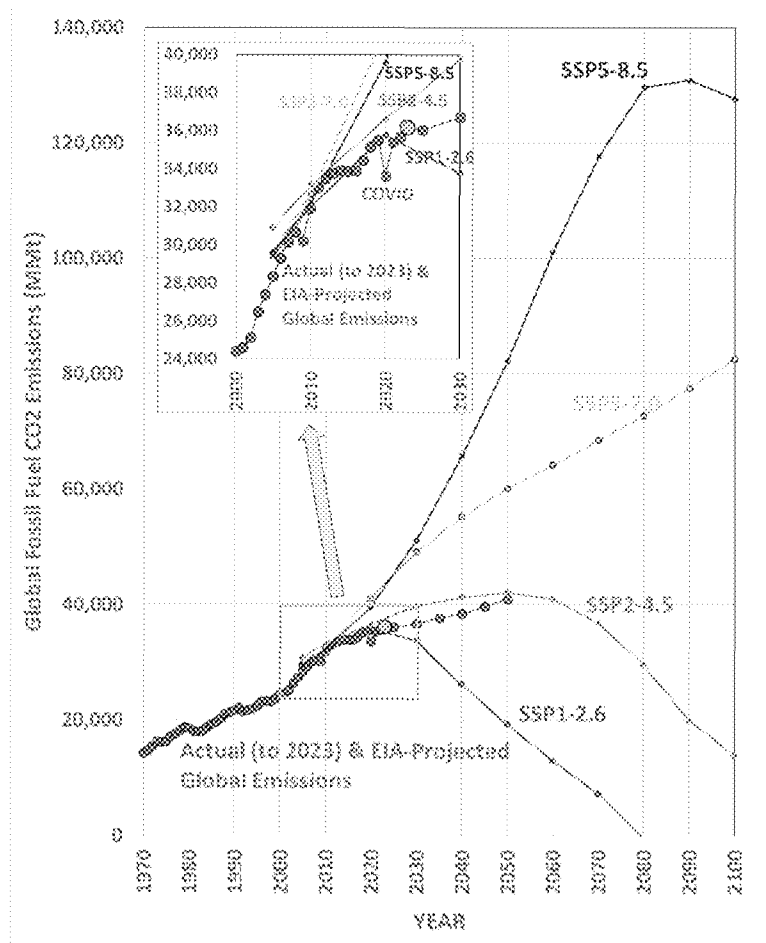
The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed trends in energy use and the near future trends diverge sharply from those of the International Energy Agency (IEA), which provides market-based projections of energy use for the coming decades. The IEA trends, which are based on plausible extrapolations of current economic and demographic trends, run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but that even lower emission scenarios are looking unlikely.

Widespread use of RCP8.5 has created an alarmist bias in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles linking RCP8.5 to the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets.

Pielke and Ritchie (2020) reported new studies using RCP8.5 were published at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude that the climate research community has spent a decade “committing scientific resources to science fiction” and that “The scientific literature has become imbalanced in an apocalyptic direction.”

The IPCC developed a new set of scenarios for AR6, the “Shared Socioeconomic Pathway” (SSP) scenarios, which have continued the bias shown in the RCP and SRES scenarios. Figure 3.3.2 shows total global observed CO<sub>2</sub> emissions compiled by the International Energy Agency (IEA) merged with the emission projection from the EIA taking account of energy use projections and current policies. The other lines show the range of IPCC SSP scenarios (SSP1-SSP5). As of 2023, global CO<sub>2</sub> emissions have been tracking well below SSP3 and higher.





**Figure 3.3.2.** Observed and projected CO<sub>2</sub> emissions. Source: IPCC (SSP scenarios) and Energy Information Administration (EIA). Green: observed historical emissions and EIA projections. Other lines: SSP1-5. Data source: Friedlingstein et al. (2024).

### 3.3.2 The carbon cycle relating emissions and concentrations

Carbon dioxide emissions from fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) have led to steadily increasing CO<sub>2</sub> concentrations in the atmosphere, as shown in Fig. 3.1.3. The relation between emissions and concentration is determined by the global carbon cycle of land and ocean processes that exchange carbon with the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021).

There are about 850 Gt of carbon (GtC) in the Earth's atmosphere<sup>2</sup>, almost all of it in the form of CO<sub>2</sub>. Each year, biological processes (plant growth and decay) and physical processes (ocean absorption and outgassing) exchange about 200 GtC of that carbon with the Earth's surface (roughly 80 GtC with the land and 120 GtC with the oceans). Before human activities became significant, removals from the atmosphere were roughly in balance with additions, as inferred from the near constancy of CO<sub>2</sub> levels in air bubbles trapped in ice cores. But burning fossil fuels (coal, oil, and gas) takes carbon out of the ground and adds it to the annual exchange. That addition (together with a much smaller contribution from cement manufacturing) amounted to 10.3 GtC in 2023, or only about 5 percent of the annual exchange.

The carbon cycle accommodates humanity's small annual injection of carbon by naturally sequestering about 50 percent of it through plant growth and oceanic uptake while the remainder accumulates in the atmosphere (Ciais et al. 2013). For that reason, the annual increase in atmospheric CO<sub>2</sub> concentration is only about half of that naively expected from human emissions.

To project future CO<sub>2</sub> concentrations in the atmosphere, and hence future human influences on the climate, it is important to know how the carbon cycle might change in the future. The historical near-constancy of that 50% fraction means that the more CO<sub>2</sub> humanity has produced, the faster Nature removed it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO<sub>2</sub> after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes that remove excess CO<sub>2</sub> from the atmosphere are increased growth of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO<sub>2</sub> by the ocean due to the increasing partial pressure of atmospheric CO<sub>2</sub> over that of CO<sub>2</sub> dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO<sub>2</sub> at an increasing rate since 1959. This is consistent with a "global greening" phenomenon (Chapter 2.1) observed by satellites since monitoring of global greenness began in the 1982.

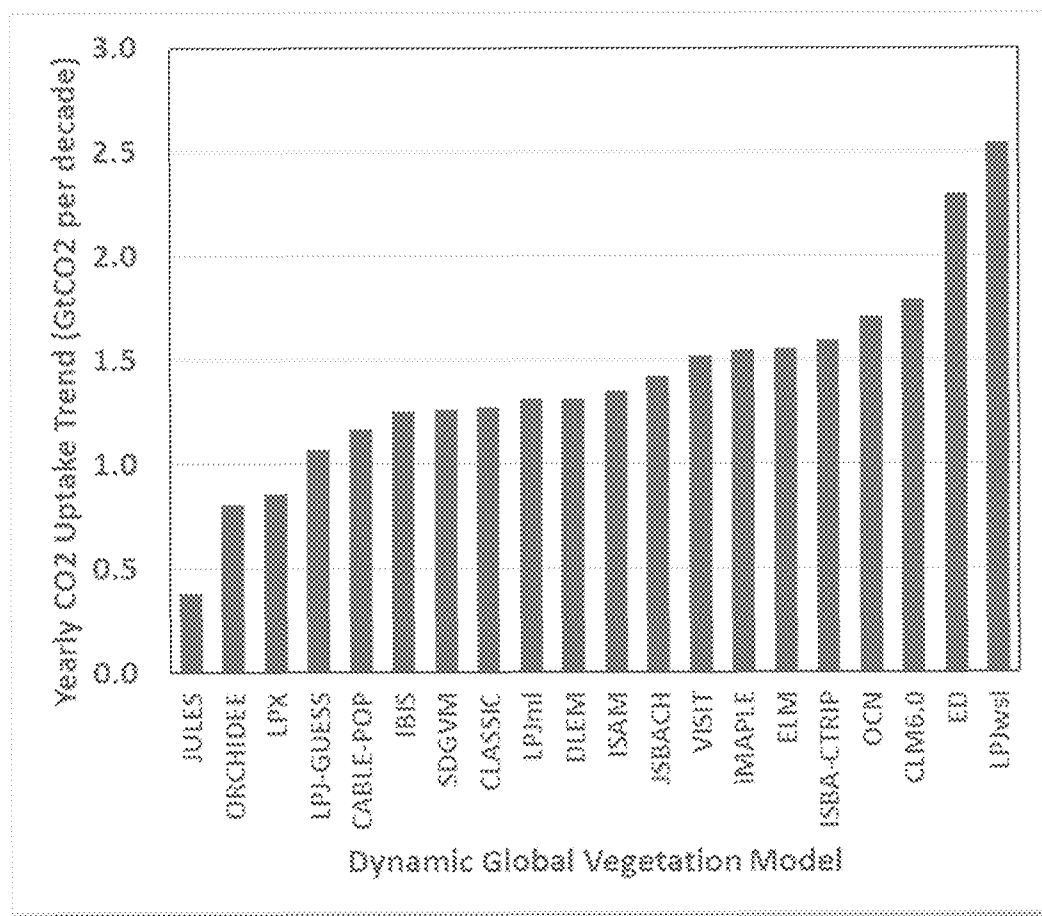
While land vegetation has been responding positively to more atmospheric CO<sub>2</sub>, uptake of extra CO<sub>2</sub> by ocean biological processes remains too uncertain to be measured reliably. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp *et al.* (2021).

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<sup>2</sup> Because CO<sub>2</sub> is chemically transformed through the course of the carbon cycle, it is more convenient to track atoms of carbon rather than molecules of CO<sub>2</sub>. One gigatonne of carbon (GtC) is equivalent to about 3.7 Gt of CO<sub>2</sub>.

### CO<sub>2</sub> uptake by land processes

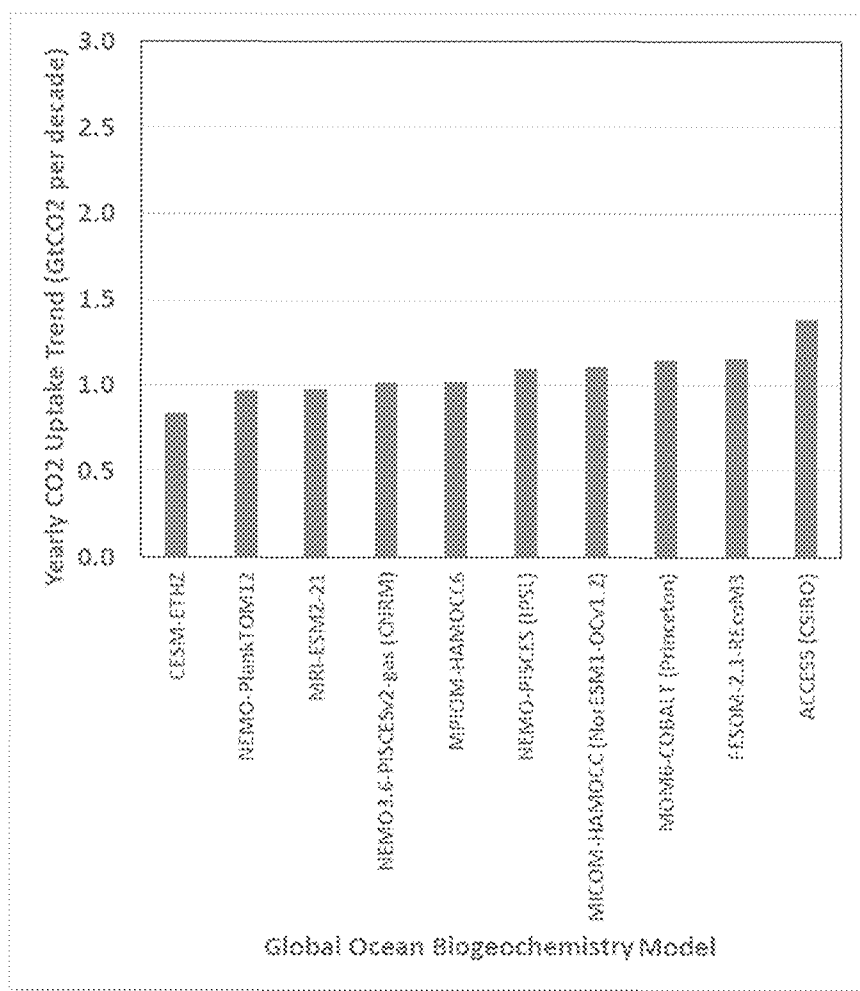
The uptake of extra CO<sub>2</sub> from the atmosphere by land surface processes (as also inferred from global greening) has been modeled with 20 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). As seen in Fig. 3.3.3, all of those models agree that vegetation and soils have been sequestering carbon from the atmosphere. But we also see that the long-term trends over 1959 to 2023 (65 years) vary widely between models, by nearly a factor of 7. This demonstrates that there remains considerable uncertainty regarding how fast CO<sub>2</sub> from the atmosphere is being removed by land processes, which in turn translates into uncertainty regarding future atmospheric CO<sub>2</sub> concentrations. Those uncertain future CO<sub>2</sub> concentrations then imply a source of uncertainty in climate model simulations of future climate change.



**Figure 3.3.3** Decadal trends in the yearly CO<sub>2</sub> uptake by land processes during 1959-2023 simulated by 20 different dynamic global vegetation models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

### CO<sub>2</sub> uptake by ocean processes

The uptake of extra CO<sub>2</sub> from the atmosphere by ocean processes has been modeled with 10 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). Like the results from the land models, all of the ocean models agree that the global oceans have been sequestering carbon from the atmosphere at an increasing rate during 1959-2023 (Fig. 3.3.4). Unlike the land models, however, the ocean models show much better agreement with each other, with the model producing the fastest increasing CO<sub>2</sub> uptake being only 65% faster than the model with the most slowly increasing CO<sub>2</sub> uptake. Note that the average trend in CO<sub>2</sub> uptake across all land models in Fig. 3.3.3 is 25% larger than the average trend in ocean uptake. This suggests land processes are increasing in their ability to remove CO<sub>2</sub> faster than ocean processes are increasing their CO<sub>2</sub> sequestration.



**Figure 3.3.5** Decadal trends in the yearly CO<sub>2</sub> uptake by ocean processes during 1959-2023 simulated by 10 different ocean biogeochemistry models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

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**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Sunday, May 18, 2025 6:40 PM  
**To:** Travis Fisher; Roy W. Spencer; John Christy; Steven Koonin; Judith Curry  
**Subject:** Link and Folder for May 19 meeting

Hello everyone:  
We meet tomorrow (May 19) 10:30 ET.

I have created a new folder called May 18 meeting drafts. I took the chapters Steve circulated which contain the cumulative comments and made a few changes:

- renumbered chapters and sections/figures as needed where subsequent mergers had happened
- moved summaries to the start of chapters
- added the tipping points material
- resolved a few queries where the material was available

I'm going to try to draft a bit of text before tomorrow's meeting on UHI for Ch 3. We don't discuss it but it deserves a mention.

Just when you have the albedo section done send it to me and indicate which chapter it should go into.

Here is the meeting info:

DoE group drafting

Monday, May 19 · 10:30am – 4:00pm

Time zone: America/Toronto

Google Meet joining info

Video call link: <https://meet.google.com/aux-jgsa-eoq>

If that link doesn't work use this one: <https://calendar.app.google/BLniCJU4uXALyMHX7>

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**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Saturday, May 17, 2025 2:33 PM  
**To:** Ross McKittrick  
**Cc:** Steven Koonin; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Re: proposed chapter merger

looks good, we can fine tune it a bit but i think it works as a combined chapter

On Sat, May 17, 2025 at 10:55 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
How's this?

On Sat, May 17, 2025 at 12:34 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Yes, a good idea, but would like to see how they get stitched together.

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**From:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>  
**Sent:** Saturday, May 17, 2025 8:51 AM  
**To:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; John Christy <[climatemanager60@gmail.com](mailto:climatemanager60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** proposed chapter merger

I propose merging the risk management chapter with heat wave mortality chapter. Both chapters are a bit skimpy, and i think they would fit well together



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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/17/2025 5:54:58 PM  
**To:** Steven Koonin [steven.koonin@gmail.com]  
**CC:** Judith Curry [curry.judith@cfanclimate.com]; John Christy [climatemanager60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: proposed chapter merger  
**Attachments:** 10 Managing Risks.May17.docx

How's this?

On Sat, May 17, 2025 at 12:34 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Yes, a good idea, but would like to see how they get stitched together.

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**From:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>  
**Sent:** Saturday, May 17, 2025 8:51 AM  
**To:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; John Christy <[climatemanager60@gmail.com](mailto:climatemanager60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** proposed chapter merger

I propose merging the risk management chapter with heat wave mortality chapter. Both chapters are a bit skimpy, and i think they would fit well together

## 10 Managing Risks of Extreme Weather

### *10.1 Socioeconomic context*

Risks from human-caused climate change are convoluted with natural weather and climate variability, and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as US population grew from 76 million in 1900 to over 331 million in 2020 (Goklany, 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01% of the US population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006% of the US population) (NOAA, 2025; USCB, 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang 2023). US weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation (NRC 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B (NBER, 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992) have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA, 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (BMI, 2013). Inland dams in the US help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages (APPA, 2024).

### *10.2 Data challenges*

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (R Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the US, so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster are down by about 80% since 1980, as a proportion of GDP. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from

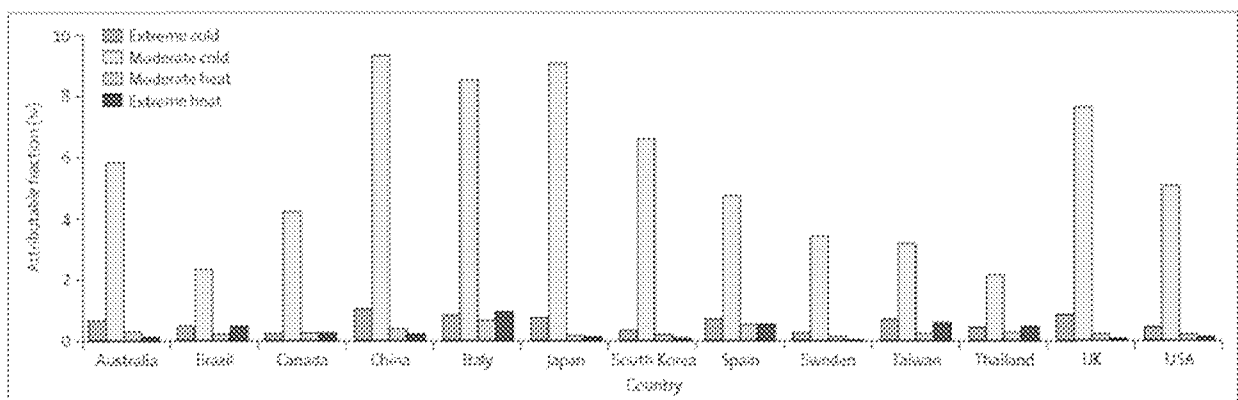
publication (R Pielke Jr., 2025).

### 10.3 Mortality from temperature extremes

#### 10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period though not in the continental US (Chapter 6) and is expected to continue with further warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes is typically caused by hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 20214). Unlike with heat-related mortality, cold-weather risks set in even at moderately cold conditions (Gasparini et al. 2015, Lee and Dessler 2023). A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7% of deaths were attributable to sub-optimal temperatures, of which 7.4% were attributable to cold and only 0.4% were attributable to heat (Gasparini et al. 2015). In other words cold weather killed 18.5 times as many people as did hot weather.



**Figure 10.3.1.** Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini et al. (2015).

Figure 10.3.1 shows the distribution of results from Gasparini et al. (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9%, of which 5.5% was due to cold, thus cold weather killed 14 times as many people as hot weather.

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86% of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis et al. (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb et al. (2014) examined mortality data for 106 million people in over 100 cities U.S. cities

and found a 60% decline in average heat-related mortality over the period 1987—2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million deaths in 211 U.S. cities from 1962 to 2006, Nordio et al. (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, by reducing mortality from cold events rising temperatures are associated with a net saving of lives.

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill et al. 2022) acknowledges that heat-related mortality risk is declining over time:

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

It is both disappointing and telling to see how the IPCC misrepresents the situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

### **10.3.2 The importance of adaptation**

The observed decline in US heat-related mortality has been specifically attributed to adaptation. Wang et al. (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live Wang et al. project not only no increase in heat-related mortality but an overall decrease for the US as a whole. They conclude that

“Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.”

### **10.3.3 Mortality risks and energy costs**

A 2016 study of US long term mortality risks associated with temperature variations (Barreca et al. 2016 ) showed that increases in mortality across the US are associated both with cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through

conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus et al. (2022) showed that wealthy and poor households in the US adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels ( $< 5^{\circ}\text{C}$ ) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days ( $>30^{\circ}\text{C}$ ) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

#### 10.4 Summary

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase as long as people are able to undertake adaptive responses.

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Saturday, May 17, 2025 12:35 PM  
**To:** 'Judith Curry'; 'Ross McKittrick'; 'John Christy'; 'Roy W. Spencer'; 'Travis Fisher'  
**Subject:** RE: proposed chapter merger

Yes, a good idea, but would like to see how they get stitched together.

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**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Saturday, May 17, 2025 8:51 AM  
**To:** Ross McKittrick <ross.mckittrick@gmail.com>; John Christy <climatemanager60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** proposed chapter merger

I propose merging the risk management chapter with heat wave mortality chapter. Both chapters are a bit skimpy, and i think they would fit well together

---

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Saturday, May 17, 2025 12:24 PM  
**To:** Judith Curry  
**Cc:** John Christy; Roy W. Spencer; Steven Koonin; Travis Fisher  
**Subject:** Re: proposed chapter merger

And they both emphasize the role of adaptive behaviour.

On Sat, May 17, 2025 at 8:51 AM Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)> wrote:

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**From:** John Christy [climateman60@gmail.com]  
**Sent:** 5/20/2025 3:55:47 PM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Steve Koonin [steven.koonin@gmail.com]; Judith Curry [curry.judith@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Obs and Models, global LT and MT, 1979-2024  
**Attachments:** LT\_MT\_CMIP6\_Obs.xlsx

Ross and Roy

Here are the annual anomalies of global LT and MT for observations and CMIP6 models. I have not put them in a common reference base, so you'll need to subtract out whatever reference period you use to put the anomalies relative to a common reference.

John C.

Global LT

|      | Sonde   | Sonde  | Sonde    | Satellite | Satellite | Satellite | Reanalysis | Reanalysis |
|------|---------|--------|----------|-----------|-----------|-----------|------------|------------|
|      | RAOBCOR | RICH   | RATPAC A | UAH_6.0   | RSS       | NOAA      | ERA5       | JRA3Q      |
| 1979 | -0.360  | -0.442 | -0.414   | -0.346    | -0.495    |           | -0.303     | -0.405     |
| 1980 | -0.213  | -0.287 | -0.275   | -0.178    | -0.344    |           | -0.235     | -0.303     |
| 1981 | -0.240  | -0.306 | -0.282   | -0.248    | -0.358    | -0.272    | -0.261     | -0.337     |
| 1982 | -0.466  | -0.530 | -0.518   | -0.433    | -0.560    | -0.393    | -0.466     | -0.481     |
| 1983 | -0.267  | -0.321 | -0.362   | -0.178    | -0.327    | -0.131    | -0.235     | -0.268     |
| 1984 | -0.533  | -0.586 | -0.567   | -0.374    | -0.590    | -0.402    | -0.504     | -0.547     |
| 1985 | -0.493  | -0.553 | -0.530   | -0.498    | -0.645    | -0.438    | -0.535     | -0.566     |
| 1986 | -0.403  | -0.481 | -0.487   | -0.356    | -0.528    | -0.274    | -0.413     | -0.430     |
| 1987 | -0.125  | -0.201 | -0.242   | -0.087    | -0.233    | 0.033     | -0.135     | -0.130     |
| 1988 | -0.112  | -0.160 | -0.196   | -0.098    | -0.264    | 0.012     | -0.090     | -0.105     |
| 1989 | -0.373  | -0.409 | -0.446   | -0.346    | -0.467    | -0.234    | -0.318     | -0.359     |
| 1990 | -0.085  | -0.113 | -0.210   | -0.124    | -0.290    | -0.015    | -0.065     | -0.119     |
| 1991 | -0.083  | -0.112 | -0.245   | -0.116    | -0.245    | 0.006     | -0.090     | -0.130     |
| 1992 | -0.414  | -0.447 | -0.512   | -0.417    | -0.518    | -0.289    | -0.376     | -0.408     |
| 1993 | -0.330  | -0.366 | -0.446   | -0.339    | -0.453    | -0.275    | -0.346     | -0.392     |
| 1994 | -0.266  | -0.297 | -0.293   | -0.201    | -0.318    | -0.152    | -0.255     | -0.265     |
| 1995 | -0.201  | -0.227 | -0.190   | -0.067    | -0.177    | -0.053    | -0.141     | -0.146     |
| 1996 | -0.324  | -0.343 | -0.369   | -0.146    | -0.278    | -0.156    | -0.246     | -0.231     |
| 1997 | -0.298  | -0.316 | -0.324   | -0.144    | -0.242    | -0.159    | -0.245     | -0.228     |
| 1998 | 0.232   | 0.220  | 0.155    | 0.347     | 0.224     | 0.306     | 0.220      | 0.260      |
| 1999 | -0.253  | -0.259 | -0.303   | -0.153    | -0.243    | -0.211    | -0.280     | -0.215     |
| 2000 | -0.284  | -0.291 | -0.326   | -0.157    | -0.248    | -0.221    | -0.315     | -0.243     |
| 2001 | -0.119  | -0.137 | -0.132   | -0.022    | -0.079    | -0.061    | -0.130     | -0.063     |
| 2002 | 0.016   | -0.006 | -0.031   | 0.080     | 0.033     | 0.035     | -0.001     | 0.033      |
| 2003 | 0.009   | -0.008 | 0.024    | 0.050     | 0.048     | 0.014     | -0.012     | 0.033      |
| 2004 | -0.088  | -0.091 | -0.081   | -0.056    | -0.024    | -0.088    | -0.104     | -0.049     |
| 2005 | 0.093   | 0.106  | 0.141    | 0.063     | 0.110     | 0.040     | 0.044      | 0.118      |
| 2006 | -0.017  | 0.000  | 0.065    | -0.023    | 0.020     | -0.044    | -0.035     | 0.018      |
| 2007 | 0.042   | 0.059  | 0.050    | 0.023     | 0.055     | 0.000     | 0.015      | -0.005     |
| 2008 | -0.254  | -0.239 | -0.199   | -0.238    | -0.153    | -0.250    | -0.240     | -0.252     |
| 2009 | -0.012  | -0.001 | 0.013    | -0.043    | 0.009     | -0.043    | -0.027     | -0.049     |
| 2010 | 0.140   | 0.151  | 0.233    | 0.194     | 0.254     | 0.197     | 0.250      | 0.223      |
| 2011 | -0.130  | -0.115 | -0.034   | -0.120    | -0.072    | -0.109    | -0.075     | -0.071     |
| 2012 | -0.059  | -0.044 | 0.022    | -0.084    | -0.006    | -0.084    | -0.035     | -0.036     |
| 2013 | 0.073   | 0.091  | 0.136    | -0.001    | 0.069     | 0.004     | 0.068      | 0.058      |

|      |       |       |       |       |       |       |       |       |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 2014 | 0.117 | 0.138 | 0.167 | 0.044 | 0.127 | 0.056 | 0.113 | 0.092 |
| 2015 | 0.270 | 0.287 | 0.302 | 0.137 | 0.260 | 0.154 | 0.221 | 0.197 |
| 2016 | 0.595 | 0.610 | 0.554 | 0.388 | 0.456 | 0.389 | 0.499 | 0.463 |
| 2017 | 0.355 | 0.373 | 0.382 | 0.265 | 0.332 | 0.240 | 0.359 | 0.307 |
| 2018 | 0.249 | 0.268 | 0.264 | 0.088 | 0.193 | 0.101 | 0.233 | 0.172 |
| 2019 | 0.470 | 0.492 | 0.481 | 0.296 | 0.401 | 0.293 | 0.437 | 0.368 |
| 2020 | 0.475 | 0.505 | 0.495 | 0.351 | 0.465 | 0.361 | 0.495 | 0.433 |
| 2021 | 0.238 | 0.275 | 0.298 | 0.138 | 0.271 | 0.184 | 0.290 | 0.234 |
| 2022 | 0.267 | 0.228 | 0.320 | 0.150 | 0.254 | 0.192 | 0.300 | 0.282 |
| 2023 | 0.515 | 0.530 | 0.573 | 0.432 | 0.551 | 0.475 | 0.585 | 0.571 |
| 2024 | 0.860 | 0.875 | 0.924 | 0.774 | 0.860 | 0.784 | 0.914 | 0.884 |
| 2025 |       |       |       |       |       |       |       |       |
| 2026 |       |       |       |       |       |       |       |       |
| 2027 |       |       |       |       |       |       |       |       |
| 2028 |       |       |       |       |       |       |       |       |
| 2029 |       |       |       |       |       |       |       |       |
| 2030 |       |       |       |       |       |       |       |       |

|      | ACCESS_C | ACCESS_E | AWI    | BCC-CSM | CAMS   | Can5   | Can5-OE | CESM   |
|------|----------|----------|--------|---------|--------|--------|---------|--------|
| 1979 | -0.190   | -0.443   | -0.313 | -0.297  | -0.210 | -0.639 | -0.613  | 0.026  |
| 1980 | -0.269   | -0.240   | -0.356 | -0.367  | -0.092 | -0.562 | -0.634  | 0.047  |
| 1981 | -0.193   | -0.293   | -0.293 | -0.137  | -0.159 | -0.395 | -0.552  | -0.486 |
| 1982 | -0.343   | -0.479   | -0.435 | -0.123  | -0.177 | -0.262 | -0.392  | -0.469 |
| 1983 | -0.458   | -0.383   | -0.433 | -0.219  | -0.178 | -0.407 | -0.596  | -0.419 |
| 1984 | -0.190   | -0.292   | -0.437 | -0.179  | -0.321 | -0.464 | -0.520  | -0.373 |
| 1985 | -0.130   | -0.488   | -0.268 | -0.373  | -0.522 | -0.496 | -0.186  | 0.052  |
| 1986 | 0.107    | -0.458   | -0.323 | -0.263  | -0.095 | -0.465 | -0.338  | -0.263 |
| 1987 | -0.319   | -0.277   | -0.140 | -0.199  | -0.017 | -0.255 | -0.359  | -0.247 |
| 1988 | -0.232   | -0.328   | -0.300 | -0.190  | -0.164 | -0.237 | -0.356  | -0.079 |
| 1989 | -0.130   | -0.247   | -0.040 | 0.002   | 0.056  | -0.218 | -0.037  | -0.088 |
| 1990 | 0.036    | -0.186   | 0.074  | -0.049  | 0.142  | -0.156 | 0.020   | -0.167 |
| 1991 | 0.041    | -0.261   | -0.226 | -0.263  | 0.014  | -0.193 | 0.012   | -0.257 |
| 1992 | -0.517   | -0.555   | -0.545 | -0.636  | -0.397 | -0.406 | -0.595  | -0.553 |
| 1993 | -0.351   | -0.325   | -0.436 | -0.377  | -0.397 | -0.559 | -0.388  | -0.270 |
| 1994 | -0.178   | -0.450   | -0.198 | -0.121  | -0.168 | -0.278 | -0.452  | 0.034  |
| 1995 | -0.193   | -0.235   | 0.061  | 0.097   | -0.060 | -0.199 | -0.224  | -0.208 |
| 1996 | -0.040   | 0.012    | 0.128  | -0.258  | -0.094 | -0.038 | 0.166   | -0.073 |
| 1997 | -0.047   | -0.014   | -0.096 | 0.134   | 0.160  | 0.138  | -0.003  | 0.183  |
| 1998 | -0.029   | 0.206    | -0.006 | -0.028  | 0.247  | 0.197  | -0.068  | -0.111 |
| 1999 | 0.101    | 0.343    | -0.020 | -0.010  | -0.019 | 0.333  | 0.128   | 0.069  |
| 2000 | 0.300    | 0.257    | 0.228  | 0.173   | 0.053  | 0.277  | 0.277   | 0.134  |
| 2001 | 0.199    | 0.458    | 0.272  | 0.324   | -0.013 | 0.263  | 0.503   | -0.051 |
| 2002 | 0.173    | 0.613    | 0.207  | 0.385   | 0.195  | 0.349  | 0.547   | 0.130  |
| 2003 | 0.366    | 0.393    | 0.368  | 0.309   | 0.318  | 0.387  | 0.464   | 0.442  |
| 2004 | 0.289    | 0.478    | 0.386  | 0.201   | 0.348  | 0.319  | 0.411   | 0.516  |
| 2005 | 0.334    | 0.443    | 0.228  | 0.300   | 0.371  | 0.405  | 0.306   | 0.335  |
| 2006 | 0.388    | 0.412    | 0.238  | 0.282   | 0.319  | 0.193  | 0.132   | 0.208  |
| 2007 | 0.097    | 0.231    | 0.406  | 0.307   | 0.287  | 0.306  | 0.326   | 0.327  |
| 2008 | 0.229    | 0.405    | 0.536  | 0.245   | 0.102  | 0.360  | 0.730   | 0.404  |
| 2009 | 0.238    | 0.493    | 0.485  | 0.342   | 0.093  | 0.552  | 0.486   | 0.524  |
| 2010 | 0.441    | 0.529    | 0.593  | 0.310   | 0.082  | 0.943  | 0.549   | 0.743  |
| 2011 | 0.555    | 0.550    | 0.352  | 0.326   | 0.231  | 0.878  | 0.577   | 0.858  |
| 2012 | 0.762    | 0.469    | 0.459  | 0.374   | 0.250  | 0.608  | 0.791   | 0.452  |
| 2013 | 0.387    | 0.666    | 0.551  | 0.443   | 0.498  | 0.807  | 0.586   | 0.500  |

|      |       |       |       |       |       |       |       |       |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 2014 | 0.542 | 0.756 | 0.491 | 0.510 | 0.398 | 0.956 | 0.814 | 0.697 |
| 2015 | 0.789 | 0.744 | 0.450 | 0.484 | 0.400 | 0.812 | 0.865 | 0.610 |
| 2016 | 0.588 | 0.663 | 0.617 | 0.466 | 0.560 | 0.754 | 0.960 | 0.659 |
| 2017 | 0.743 | 0.832 | 0.716 | 0.608 | 0.353 | 1.030 | 0.862 | 0.841 |
| 2018 | 0.928 | 0.858 | 0.727 | 0.630 | 0.467 | 0.945 | 0.852 | 0.661 |
| 2019 | 0.778 | 0.656 | 0.773 | 0.506 | 0.562 | 0.875 | 1.173 | 0.613 |
| 2020 | 0.868 | 0.621 | 0.579 | 0.673 | 0.600 | 1.237 | 1.105 | 0.656 |
| 2021 | 0.864 | 0.561 | 0.817 | 0.694 | 0.811 | 1.107 | 1.291 | 0.599 |
| 2022 | 1.081 | 0.832 | 0.940 | 0.734 | 0.691 | 1.087 | 1.221 | 0.796 |
| 2023 | 0.952 | 0.906 | 0.961 | 0.791 | 0.397 | 1.237 | 1.275 | 1.226 |
| 2024 | 1.101 | 1.064 | 0.956 | 0.680 | 0.449 | 1.293 | 1.265 | 1.034 |
| 2025 | 1.176 | 0.961 | 0.908 | 0.637 | 0.680 | 1.497 | 1.475 | 1.173 |
| 2026 | 1.096 | 1.221 | 0.954 | 0.953 | 0.462 | 1.794 | 1.604 | 1.253 |
| 2027 | 1.271 | 1.319 | 0.900 | 0.940 | 0.657 | 1.622 | 1.507 | 0.679 |
| 2028 | 1.357 | 1.294 | 0.967 | 1.031 | 0.458 | 1.517 | 1.544 | 0.991 |
| 2029 | 1.352 | 1.426 | 1.002 | 0.925 | 0.303 | 1.465 | 1.785 | 1.064 |
| 2030 | 1.274 | 1.257 | 1.039 | 1.004 | 0.283 | 1.477 | 1.624 | 1.224 |

| CESM2-W | CIESM  | CIESM  | CNRM-CN | CNRM_HI | CNRM-ES | EC-EARTH | EC-E3-VE | FGOALS-f | FGOALS-g |
|---------|--------|--------|---------|---------|---------|----------|----------|----------|----------|
| -0.288  | -0.434 | -0.250 | -0.334  | -0.282  | -0.153  | -0.018   | -0.453   | -0.416   | -0.399   |
| -0.459  | -0.277 | -0.048 | -0.117  | -0.232  | -0.238  | 0.112    | -0.262   | -0.130   | -0.158   |
| -0.093  | -0.155 | -0.030 | -0.194  | -0.175  | -0.339  | -0.288   | 0.028    | -0.151   | -0.198   |
| -0.222  | -0.428 | -0.246 | -0.335  | -0.051  | -0.282  | -0.372   | -0.396   | -0.395   | -0.273   |
| -0.554  | -0.561 | -0.169 | -0.200  | -0.421  | -0.171  | -0.472   | -0.484   | -0.290   | -0.410   |
| -0.285  | -0.254 | -0.125 | -0.357  | -0.389  | -0.274  | -0.058   | -0.293   | -0.217   | -0.392   |
| -0.325  | -0.060 | -0.298 | -0.261  | -0.175  | -0.269  | -0.416   | -0.333   | -0.622   | -0.305   |
| -0.501  | -0.357 | -0.406 | -0.288  | -0.330  | 0.001   | -0.476   | -0.273   | -0.218   | -0.497   |
| -0.471  | -0.231 | -0.181 | -0.048  | -0.188  | -0.191  | -0.311   | -0.335   | -0.076   | -0.108   |
| -0.132  | -0.083 | -0.104 | -0.037  | -0.157  | -0.061  | -0.107   | -0.328   | -0.344   | 0.005    |
| -0.038  | -0.148 | -0.148 | -0.110  | -0.053  | -0.238  | 0.117    | -0.174   | -0.184   | -0.197   |
| -0.223  | 0.046  | -0.047 | 0.023   | -0.046  | -0.165  | 0.205    | -0.005   | 0.206    | -0.064   |
| -0.323  | 0.111  | 0.166  | -0.056  | -0.061  | 0.077   | -0.163   | 0.215    | -0.250   | 0.052    |
| -0.199  | -0.454 | -0.454 | -0.236  | -0.209  | -0.192  | -0.755   | -0.570   | -0.547   | -0.633   |
| -0.147  | -0.455 | -0.433 | -0.006  | -0.145  | -0.255  | -0.663   | -0.530   | -0.057   | -0.481   |
| -0.158  | -0.172 | -0.550 | -0.369  | -0.028  | 0.176   | -0.346   | -0.214   | -0.015   | -0.158   |
| -0.122  | 0.079  | -0.463 | -0.210  | -0.062  | -0.111  | 0.105    | -0.134   | -0.147   | -0.301   |
| -0.131  | -0.151 | -0.273 | 0.114   | -0.023  | -0.031  | -0.255   | 0.058    | 0.026    | -0.115   |
| -0.024  | 0.015  | -0.164 | -0.183  | 0.063   | 0.116   | -0.144   | 0.213    | 0.145    | 0.220    |
| -0.089  | 0.185  | -0.096 | 0.077   | 0.003   | -0.146  | 0.007    | 0.315    | 0.110    | 0.024    |
| 0.046   | 0.249  | -0.077 | 0.119   | 0.115   | 0.158   | 0.183    | 0.082    | 0.187    | 0.093    |
| 0.275   | 0.033  | -0.031 | 0.241   | -0.010  | 0.043   | 0.272    | 0.051    | 0.074    | 0.232    |
| 0.498   | 0.186  | 0.185  | 0.335   | 0.077   | 0.017   | 0.258    | 0.285    | 0.110    | 0.112    |
| 0.420   | 0.372  | 0.445  | 0.263   | 0.152   | 0.053   | 0.241    | 0.279    | 0.416    | 0.347    |
| 0.407   | 0.117  | 0.542  | 0.166   | 0.262   | 0.249   | 0.277    | 0.345    | 0.122    | 0.356    |
| 0.319   | 0.155  | 0.241  | 0.353   | 0.120   | 0.037   | 0.204    | 0.435    | 0.387    | 0.451    |
| 0.247   | 0.405  | 0.197  | -0.058  | 0.251   | 0.310   | 0.639    | 0.262    | 0.513    | 0.395    |
| 0.211   | 0.546  | 0.357  | 0.137   | 0.142   | 0.074   | 0.687    | 0.345    | -0.057   | 0.324    |
| 0.498   | 0.245  | 0.537  | 0.501   | 0.300   | 0.522   | 0.301    | 0.415    | 0.306    | 0.357    |
| 0.488   | 0.155  | 0.633  | 0.316   | 0.285   | 0.390   | 0.296    | 0.290    | 0.672    | 0.311    |
| 0.252   | 0.252  | 0.543  | 0.130   | 0.300   | 0.096   | 0.377    | 0.187    | 0.085    | 0.487    |
| 0.380   | 0.371  | 0.441  | 0.181   | 0.450   | 0.402   | 0.645    | 0.268    | 0.201    | 0.356    |
| 0.550   | 0.262  | 0.502  | 0.311   | 0.301   | 0.489   | 0.413    | 0.382    | 0.537    | 0.381    |
| 0.672   | 0.338  | 0.597  | 0.487   | 0.425   | 0.330   | 0.497    | 0.574    | 0.357    | 0.524    |
| 0.508   | 0.551  | 0.670  | 0.306   | 0.379   | 0.560   | 0.606    | 0.440    | 0.462    | 0.234    |

|       |       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.537 | 0.604 | 0.466 | 0.415 | 0.434 | 0.530 | 0.786 | 0.545 | 0.626 | 0.518 |
| 0.707 | 0.218 | 0.616 | 0.420 | 0.530 | 0.459 | 0.393 | 0.594 | 0.372 | 0.235 |
| 0.857 | 0.256 | 0.928 | 0.590 | 0.406 | 0.705 | 0.525 | 0.606 | 0.514 | 0.778 |
| 0.845 | 0.563 | 0.989 | 0.706 | 0.519 | 0.593 | 0.402 | 0.686 | 0.457 | 0.781 |
| 0.957 | 0.680 | 0.242 | 0.377 | 0.725 | 0.668 | 0.671 | 0.798 | 0.523 | 0.772 |
| 0.582 | 0.625 | 0.033 | 0.532 | 0.654 | 0.866 | 0.770 | 0.908 | 0.885 | 0.785 |
| 0.489 | 0.561 | 0.009 | 0.767 | 0.605 | 0.684 | 0.459 | 0.923 | 0.730 | 0.632 |
| 0.927 | 0.687 | 0.488 | 0.722 | 0.621 | 0.825 | 0.575 | 0.694 | 0.549 | 0.505 |
| 1.044 | 0.739 | 0.820 | 0.849 | 0.747 | 0.594 | 0.808 | 0.674 | 1.009 | 0.664 |
| 0.772 | 0.853 | 0.697 | 0.746 | 0.807 | 0.952 | 0.609 | 0.745 | 1.018 | 0.607 |
| 0.933 | 0.633 | 0.706 | 0.829 | 0.968 | 1.165 | 0.744 | 0.913 | 0.633 | 0.957 |
| 1.181 | 0.816 | 0.616 | 0.978 | 0.530 | 0.970 | 0.835 | 1.019 | 1.024 | 0.748 |
| 1.092 | 1.064 | 0.679 | 0.783 | 0.406 | 1.090 | 0.850 | 0.724 | 1.161 | 0.852 |
| 1.027 | 0.967 | 0.856 | 0.923 | 0.519 | 1.039 | 0.723 | 0.833 | 0.689 | 0.751 |
| 1.268 | 1.113 | 1.047 | 1.127 | 0.725 | 1.228 | 0.717 | 0.867 | 0.948 | 0.681 |
| 1.467 | 1.101 | 0.924 | 0.767 | 0.654 | 0.930 | 0.827 | 0.957 | 1.190 | 0.944 |
| 1.062 | 1.127 | 0.859 | 0.909 | 0.605 | 1.183 | 0.993 | 1.057 | 0.929 | 0.783 |



| FIO    | GFDL-CM | GFDL-ESM | GISS   | HadGEM | IITM   | INM-CM4 | INM-CM5 | IPSL-CM6 | KACE   |
|--------|---------|----------|--------|--------|--------|---------|---------|----------|--------|
| -0.498 | -0.173  | -0.194   | 0.009  | -0.460 | -0.199 | -0.148  | -0.136  | -0.296   | -0.472 |
| -0.409 | -0.212  | -0.394   | -0.077 | -0.349 | -0.308 | -0.197  | -0.104  | -0.195   | -0.321 |
| -0.363 | -0.538  | -0.187   | -0.289 | -0.456 | -0.273 | -0.187  | -0.237  | -0.178   | -0.207 |
| -0.488 | -0.322  | 0.057    | -0.412 | -0.350 | -0.214 | -0.245  | -0.208  | -0.569   | -0.403 |
| -0.600 | -0.359  | -0.389   | -0.089 | -0.497 | -0.296 | -0.667  | -0.636  | -0.695   | -0.487 |
| -0.267 | -0.369  | -0.440   | 0.013  | -0.248 | -0.092 | -0.398  | -0.458  | -0.509   | -0.239 |
| -0.148 | -0.504  | -0.419   | -0.425 | -0.392 | -0.322 | -0.264  | -0.401  | -0.653   | -0.363 |
| -0.399 | -0.250  | -0.228   | -0.572 | -0.264 | -0.171 | -0.218  | -0.195  | -0.378   | -0.216 |
| -0.193 | 0.053   | -0.234   | -0.325 | -0.345 | 0.036  | -0.232  | -0.213  | -0.039   | -0.193 |
| -0.098 | -0.104  | -0.298   | 0.137  | -0.303 | -0.016 | -0.120  | -0.129  | 0.136    | -0.024 |
| -0.029 | -0.079  | -0.156   | 0.263  | -0.227 | -0.154 | -0.026  | -0.013  | 0.405    | -0.150 |
| 0.184  | -0.113  | 0.211    | 0.147  | -0.047 | 0.010  | 0.069   | 0.001   | -0.121   | 0.020  |
| 0.020  | -0.135  | 0.144    | -0.147 | 0.001  | 0.092  | 0.056   | 0.084   | -0.278   | -0.146 |
| -0.289 | -0.410  | -0.635   | -0.652 | -0.336 | -0.382 | -0.461  | -0.386  | -0.342   | -0.403 |
| -0.307 | -0.396  | -0.554   | -0.344 | -0.377 | -0.163 | -0.468  | -0.459  | -0.340   | -0.338 |
| -0.301 | -0.376  | -0.118   | 0.166  | -0.384 | -0.280 | -0.274  | -0.237  | -0.138   | -0.174 |
| -0.154 | -0.217  | -0.118   | -0.111 | -0.248 | -0.143 | -0.057  | -0.091  | -0.001   | -0.141 |
| -0.021 | -0.063  | -0.126   | -0.390 | -0.119 | -0.110 | 0.021   | -0.035  | 0.125    | -0.064 |
| -0.007 | 0.124   | 0.002    | -0.091 | -0.041 | -0.106 | 0.078   | 0.116   | 0.139    | 0.027  |
| 0.061  | 0.105   | 0.027    | 0.212  | 0.023  | -0.040 | 0.106   | 0.153   | -0.048   | 0.021  |
| 0.119  | -0.034  | 0.166    | 0.287  | 0.011  | 0.100  | 0.210   | 0.151   | 0.056    | 0.130  |
| 0.237  | 0.258   | 0.222    | -0.142 | 0.122  | 0.241  | 0.268   | 0.191   | 0.268    | 0.065  |
| 0.393  | 0.331   | 0.322    | -0.182 | 0.315  | 0.313  | 0.246   | 0.193   | 0.181    | 0.130  |
| 0.126  | 0.232   | 0.365    | 0.210  | 0.439  | 0.108  | 0.139   | 0.250   | 0.113    | 0.270  |
| 0.148  | 0.236   | 0.195    | 0.279  | 0.265  | 0.310  | 0.272   | 0.319   | 0.105    | 0.341  |
| 0.238  | 0.459   | 0.349    | 0.037  | 0.423  | 0.283  | 0.336   | 0.371   | 0.083    | 0.355  |
| 0.422  | 0.333   | 0.300    | -0.010 | 0.405  | 0.369  | 0.273   | 0.323   | 0.435    | 0.324  |
| 0.369  | 0.447   | 0.109    | 0.289  | 0.614  | 0.235  | 0.253   | 0.326   | 0.497    | 0.243  |
| 0.333  | 0.479   | 0.213    | 0.623  | 0.542  | 0.362  | 0.261   | 0.325   | 0.176    | 0.351  |
| 0.300  | 0.469   | 0.352    | 0.569  | 0.305  | -0.037 | 0.270   | 0.277   | 0.126    | 0.384  |
| 0.346  | 0.270   | 0.506    | 0.575  | 0.476  | 0.102  | 0.339   | 0.354   | 0.635    | 0.421  |
| 0.362  | 0.479   | 0.348    | 0.374  | 0.685  | 0.246  | 0.425   | 0.277   | 0.822    | 0.453  |
| 0.434  | 0.632   | 0.348    | 0.217  | 0.910  | 0.349  | 0.387   | 0.258   | 0.324    | 0.492  |
| 0.397  | 0.565   | 0.578    | 0.468  | 0.831  | 0.466  | 0.384   | 0.319   | 0.595    | 0.494  |
| 0.227  | 0.531   | 0.799    | 0.526  | 0.637  | 0.201  | 0.461   | 0.346   | 0.634    | 0.451  |

|       |       |       |        |       |       |       |       |       |       |
|-------|-------|-------|--------|-------|-------|-------|-------|-------|-------|
| 0.367 | 0.672 | 0.381 | -0.041 | 0.886 | 0.372 | 0.352 | 0.309 | 0.378 | 0.579 |
| 0.476 | 0.763 | 0.379 | 0.026  | 0.968 | 0.427 | 0.379 | 0.454 | 0.340 | 0.768 |
| 0.612 | 0.666 | 0.576 | 0.566  | 1.007 | 0.594 | 0.356 | 0.469 | 0.442 | 0.778 |
| 0.546 | 0.529 | 0.777 | 0.813  | 0.945 | 0.278 | 0.425 | 0.432 | 0.812 | 0.967 |
| 0.650 | 0.625 | 0.902 | 0.422  | 1.067 | 0.445 | 0.356 | 0.397 | 0.874 | 0.864 |
| 0.853 | 0.645 | 0.990 | 0.154  | 0.989 | 0.597 | 0.461 | 0.502 | 0.627 | 1.002 |
| 0.681 | 0.740 | 0.499 | 0.410  | 1.075 | 0.336 | 0.544 | 0.459 | 0.758 | 1.003 |
| 0.837 | 0.757 | 0.579 | 0.943  | 1.242 | 0.522 | 0.606 | 0.634 | 0.836 | 1.197 |
| 0.767 | 0.975 | 0.796 | 0.916  | 1.536 | 0.533 | 0.595 | 0.676 | 0.591 | 1.233 |
| 0.824 | 0.926 | 0.968 | 0.862  | 1.348 | 0.199 | 0.603 | 0.600 | 0.716 | 1.240 |
| 0.655 | 0.923 | 0.977 | 0.682  | 1.385 | 0.517 | 0.842 | 0.755 | 0.960 | 1.302 |
| 0.730 | 1.018 | 0.861 | 1.069  | 1.503 | 0.636 | 0.799 | 0.700 | 1.029 | 1.396 |
| 0.968 | 1.196 | 1.057 | 1.206  | 1.541 | 0.938 | 0.830 | 0.703 | 1.184 | 1.410 |
| 0.948 | 1.047 | 0.904 | 0.659  | 1.544 | 0.507 | 0.788 | 0.746 | 1.036 | 1.431 |
| 1.000 | 1.080 | 0.844 | 0.338  | 1.626 | 0.779 | 0.799 | 0.858 | 0.931 | 1.493 |
| 0.928 | 1.219 | 0.864 | 0.681  | 1.627 | 0.704 | 0.820 | 0.808 | 0.996 | 1.498 |
| 0.925 | 1.354 | 1.065 | 1.170  | 1.504 | 0.566 | 0.823 | 0.924 | 0.810 | 1.498 |

| KIOST  | MCM-UA | MIROC6 | MIROC6-1 | MPI-HR | MPI-LR | MRI-ESM | NESM   | NOR-LM | UKESM1 |
|--------|--------|--------|----------|--------|--------|---------|--------|--------|--------|
| -0.248 | -0.458 | -0.170 | -0.287   | -0.274 | -0.439 | -0.237  | -0.287 | -0.450 | -0.480 |
| -0.488 | -0.397 | -0.410 | 0.019    | 0.043  | -0.117 | -0.366  | -0.346 | -0.285 | -0.564 |
| -0.348 | -0.394 | -0.475 | 0.161    | -0.085 | -0.178 | -0.174  | -0.221 | -0.261 | -0.433 |
| -0.286 | -0.452 | -0.146 | -0.458   | -0.238 | -0.351 | -0.131  | -0.217 | -0.127 | -0.390 |
| -0.406 | -0.557 | -0.131 | -0.626   | -0.394 | -0.466 | -0.265  | -0.733 | -0.065 | -0.484 |
| -0.533 | -0.327 | 0.191  | -0.312   | -0.309 | -0.174 | -0.407  | -0.377 | -0.203 | -0.398 |
| -0.323 | -0.265 | -0.097 | 0.112    | -0.143 | -0.062 | -0.053  | -0.503 | -0.333 | -0.508 |
| -0.268 | -0.290 | -0.432 | 0.188    | 0.076  | -0.030 | -0.049  | -0.407 | -0.186 | -0.314 |
| -0.189 | -0.312 | -0.176 | -0.371   | 0.001  | -0.223 | -0.213  | -0.321 | -0.384 | -0.303 |
| 0.127  | -0.190 | -0.045 | -0.373   | -0.023 | -0.306 | -0.009  | -0.159 | -0.395 | -0.437 |
| -0.144 | -0.262 | -0.158 | -0.231   | -0.084 | -0.205 | -0.235  | 0.046  | -0.163 | -0.184 |
| 0.012  | -0.178 | -0.129 | 0.093    | -0.018 | 0.004  | -0.178  | 0.203  | -0.074 | -0.004 |
| 0.246  | -0.285 | -0.165 | 0.412    | -0.164 | 0.020  | -0.021  | 0.007  | 0.038  | -0.260 |
| -0.682 | -0.397 | -0.455 | -0.530   | -0.497 | -0.406 | -0.453  | -0.569 | -0.338 | -0.698 |
| -0.233 | -0.301 | -0.177 | -0.713   | -0.408 | -0.136 | -0.277  | -0.514 | -0.490 | -0.434 |
| -0.379 | -0.248 | 0.128  | -0.378   | -0.064 | -0.213 | -0.212  | -0.128 | -0.367 | -0.090 |
| -0.181 | -0.214 | -0.307 | -0.021   | 0.025  | -0.339 | -0.023  | -0.161 | -0.198 | -0.128 |
| -0.010 | 0.075  | -0.474 | 0.168    | -0.078 | -0.064 | -0.223  | -0.045 | -0.047 | -0.082 |
| -0.263 | 0.279  | -0.210 | 0.383    | -0.247 | 0.250  | -0.097  | -0.033 | 0.120  | 0.028  |
| 0.073  | 0.250  | -0.076 | -0.219   | -0.023 | 0.127  | 0.111   | 0.202  | 0.205  | 0.288  |
| 0.176  | 0.280  | 0.416  | -0.321   | 0.066  | 0.146  | 0.005   | 0.379  | 0.276  | 0.218  |
| 0.132  | 0.396  | 0.252  | -0.070   | 0.087  | 0.107  | 0.093   | 0.214  | 0.446  | 0.252  |
| 0.372  | 0.252  | 0.086  | 0.384    | 0.251  | 0.035  | 0.331   | 0.061  | 0.529  | 0.305  |
| 0.012  | 0.220  | -0.015 | 0.200    | 0.315  | 0.090  | 0.057   | 0.361  | 0.023  | 0.548  |
| 0.183  | 0.402  | 0.306  | 0.122    | 0.142  | 0.391  | 0.049   | 0.418  | -0.032 | 0.263  |
| 0.380  | 0.637  | 0.628  | 0.659    | 0.109  | 0.319  | 0.200   | 0.325  | 0.171  | 0.313  |
| 0.338  | 0.618  | 0.211  | 0.658    | 0.117  | 0.107  | 0.520   | 0.263  | 0.145  | 0.417  |
| 0.217  | 0.185  | 0.049  | -0.054   | 0.240  | 0.135  | 0.332   | 0.405  | 0.044  | 0.450  |
| 0.287  | 0.298  | 0.101  | -0.115   | 0.176  | 0.329  | 0.319   | 0.326  | 0.248  | 0.478  |
| 0.664  | 0.332  | 0.537  | 0.156    | 0.356  | 0.451  | 0.451   | 0.443  | 0.460  | 0.467  |
| 0.646  | 0.257  | 0.690  | 0.324    | 0.461  | 0.319  | 0.339   | 0.395  | 0.502  | 0.517  |
| 0.371  | 0.180  | 0.062  | 0.773    | 0.340  | 0.325  | 0.201   | 0.334  | 0.445  | 0.596  |
| 0.708  | 0.329  | 0.039  | 0.383    | 0.416  | 0.390  | 0.194   | 0.683  | 0.593  | 0.642  |
| 0.803  | 0.654  | 0.240  | 0.164    | 0.521  | 0.437  | 0.380   | 0.780  | 0.484  | 0.615  |
| 0.664  | 0.744  | 0.799  | 0.265    | 0.598  | 0.293  | 0.412   | 0.885  | 0.592  | 0.687  |

|       |       |        |       |       |       |       |       |       |       |
|-------|-------|--------|-------|-------|-------|-------|-------|-------|-------|
| 0.813 | 0.731 | 0.724  | 0.519 | 0.494 | 0.275 | 0.338 | 0.522 | 0.870 | 0.826 |
| 0.613 | 0.895 | 0.044  | 0.894 | 0.312 | 0.400 | 0.522 | 0.912 | 0.597 | 0.797 |
| 0.409 | 0.856 | -0.057 | 0.283 | 0.345 | 0.527 | 0.628 | 0.839 | 0.508 | 0.982 |
| 0.484 | 0.629 | 0.314  | 0.177 | 0.282 | 0.529 | 0.851 | 0.822 | 0.593 | 0.840 |
| 0.373 | 0.403 | 0.762  | 0.387 | 0.493 | 0.403 | 0.519 | 0.879 | 0.728 | 0.841 |
| 0.687 | 0.337 | 0.353  | 0.707 | 0.747 | 0.171 | 0.475 | 0.954 | 0.923 | 1.051 |
| 0.472 | 0.468 | 0.236  | 1.063 | 0.674 | 0.360 | 0.593 | 1.031 | 0.873 | 1.140 |
| 0.838 | 0.695 | 0.289  | 0.650 | 0.714 | 0.815 | 0.677 | 1.347 | 0.746 | 0.867 |
| 0.593 | 0.815 | 0.423  | 0.879 | 0.815 | 0.607 | 1.008 | 1.201 | 0.948 | 1.120 |
| 0.773 | 0.700 | 0.676  | 1.281 | 0.632 | 0.573 | 1.040 | 1.275 | 0.634 | 1.348 |
| 0.996 | 0.653 | 1.004  | 0.884 | 0.788 | 0.840 | 0.896 | 1.372 | 0.511 | 1.304 |
| 0.537 | 0.909 | 0.513  | 0.479 | 0.838 | 0.608 | 0.910 | 1.490 | 0.531 | 1.444 |
| 0.923 | 0.904 | 0.500  | 0.516 | 0.514 | 0.556 | 1.050 | 1.229 | 0.396 | 1.381 |
| 1.010 | 0.851 | 0.674  | 0.733 | 0.560 | 0.532 | 1.078 | 1.097 | 0.431 | 1.376 |
| 0.777 | 0.828 | 1.041  | 1.100 | 0.678 | 0.711 | 1.088 | 0.962 | 0.789 | 1.422 |
| 1.041 | 0.909 | 1.293  | 1.289 | 0.952 | 0.795 | 1.187 | 1.235 | 0.998 | 1.558 |
| 0.979 | 1.085 | 0.602  | 0.629 | 0.795 | 0.950 | 0.943 | 1.201 | 0.986 | 1.579 |

---

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 20, 2025 7:51 AM  
**To:** 'Roy Spencer'; 'Ross McKittrick'  
**Cc:** 'Judith Curry'; 'John Christy'; 'Travis Fisher'  
**Subject:** RE: Ross, please insert this comparison of the 20 vegetation models' CO2 uptake trends...

Like this.

In either the text or caption, we should remark on the smallness of these numbers (about 0.1 Gt CO2 per year) relative to both the annual CO2 exchange between land/atmosphere (about 450 Gt CO2) and the current annual anthropogenic emissions (37 Gt CO2).

The same will hold for the ocean numbers.

Implication is that we are looking for signal in the noise and small, potentially unknown/unmeasurable effects are important. Analogous to the radiative forcing discussion.

SEK

---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Tuesday, May 20, 2025 7:34 AM  
**To:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Cc:** Steve Koonin <steven.koonin@gmail.com>; Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Ross, please insert this comparison of the 20 vegetation models' CO2 uptake trends...

...into the carbon cycle chapter where appropriate. As Judy pointed out, there are large variations among models. I will do the ocean models next.

---

**From:** Roy Spencer [roywspencer@hotmail.com]  
**Sent:** 5/20/2025 11:33:58 AM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]  
**CC:** Steve Koonin [steven.koonin@gmail.com]; Judith Curry [curry.judith@gmail.com]; John Christy [climateman60@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Ross, please insert this comparison of the 20 vegetation models' CO2 uptake trends ...  
**Attachments:** The uptake of extra CO2 from the atmosphere by land surface processes [RS].docx

...into the carbon cycle chapter where appropriate. As Judy pointed out, there are large variations among models. I will do the ocean models next.

The uptake of extra CO<sub>2</sub> from the atmosphere by land surface processes (as also inferred from global greening) has been modeled with 20 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). As seen in Fig. x.x.x, all of those models agree that vegetation and soils have been sequestering carbon from the atmosphere. But we also see that the long-term trends over 1959 to 2023 (65 years) vary widely between models, by nearly a factor of 7. This demonstrates that there remains considerable uncertainty regarding how fast CO<sub>2</sub> from the atmosphere is being removed by land processes, which in turn translates into uncertainty regarding future atmospheric CO<sub>2</sub> concentrations. Those uncertain future CO<sub>2</sub> concentrations then imply a source of uncertainty in climate model simulations of future climate change.

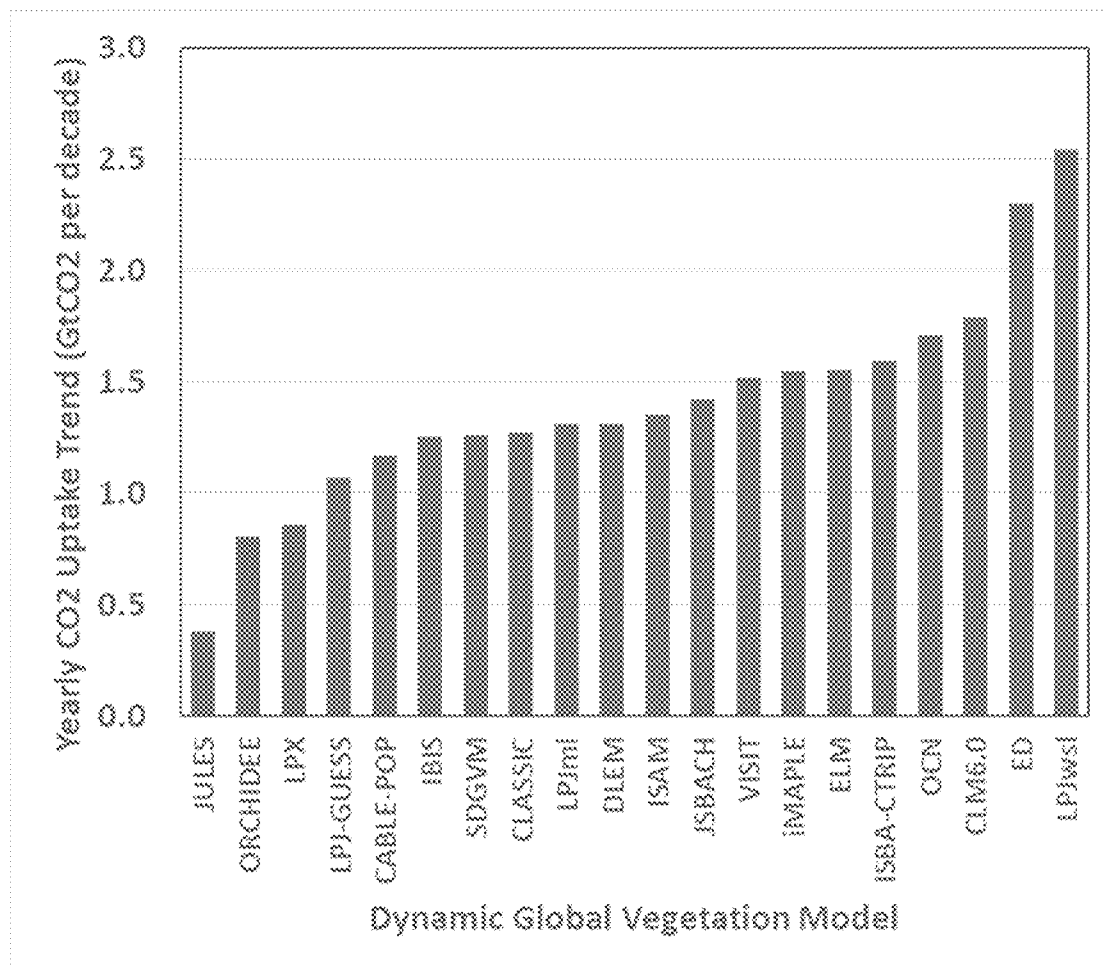


Fig. x.x.x Decadal trends in the yearly CO<sub>2</sub> uptake by land processes during 1959-2023 simulated by 20 different dynamic global vegetation models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

Friedlingstein, P., and 95 co-authors (2024): Global Carbon Budget 2024, Earth Syst. Sci. Data, <https://essd.copernicus.org/preprints/essd-2024-519>, 2024





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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/21/2025 2:33:16 PM  
**To:** Steven Koonin [steven.koonin@gmail.com]  
**CC:** Judith Curry [curry.judith@gmail.com]; John Christy [climateman60@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: ch 4 revisions  
**Attachments:** ~WRD0005.jpg

I found the part about lapse rate interacting with water vapor hard to follow. How is this rewording of the two paragraphs:

By itself, the equilibrium warming effect of a doubling of atmospheric CO<sub>2</sub> is slightly more than 1°C (Soden and Held 2006). The large values of ECS arise from positive feedbacks that amplify the CO<sub>2</sub> warming. Water vapor feedback is positive: a warmer atmosphere may have more water vapor, which itself is a powerful greenhouse gas. Warmer temperatures also result in less snow and sea ice cover, allowing the Earth to absorb more of the sun's radiation. Some simple estimates of these feedbacks increase the ECS to around 2°C (Sherwood et al., 2020).

Higher values of ECS arise primarily from positive cloud feedbacks whose magnitude, and even sign, are highly uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for climate models to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

On Wed, May 21, 2025 at 10:20 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Easiest for me to think about it as follows:

Forcing from CO<sub>2</sub> is (5.4 W/m<sup>2</sup>) ln (C/C<sub>0</sub>). For doubling CO<sub>2</sub>, the ln is 0.7, giving a forcing of 3.8 W/m<sup>2</sup>

The Black Body (Boltzmann) feedback parameter for all models is about -3.3 (W/m<sup>2</sup>)/K, as can be directly computed from the SB law.. So the direct temperature rise is 3.8/3.3 or about 1.2 K.

Feedbacks then come on top of this, allegedly to double or triple the sensitivity

---

**From:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>  
**Sent:** Wednesday, May 21, 2025 10:07 AM  
**To:** Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Cc:** Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** Re: ch 4 revisions

Hall and Manabe 1997 (attached, Fig 3) is the one I use to make the point about 1C direct effect from CO<sub>2</sub> doubling. Yesterday we were debating the forcing amount from CO<sub>2</sub> doubling.

On Wed, May 21, 2025 at 10:03 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
What is the citation indicated as a superscript 33?

On Wed, May 21, 2025 at 9:31 AM Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:  
attached, added text in red

--



Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

---

**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Wednesday, May 21, 2025 10:21 AM  
**To:** Ross McKittrick  
**Subject:** Re: ch 4 revisions

that is fine also

On Wed, May 21, 2025 at 7:07 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
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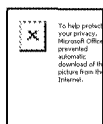
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**Sent:** Wednesday, May 21, 2025 10:21 AM  
**To:** Ross McKittrick  
**Subject:** Re: ch 4 revisions

Brian J. Soden and Isaac M. Held, "An Assessment of Climate Feedbacks in Coupled Ocean–Atmosphere Models," *Journal of Climate* 19, no. 14 ( July 15, 2006): 3354–3360, <https://doi.org/10.1175/jcli3799.1>.

On Wed, May 21, 2025 at 7:04 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
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<http://www.cfanclimate.net>

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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/21/2025 2:20:22 PM  
**To:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]  
**CC:** 'John Christy' [climateman60@gmail.com]; 'Roy Spencer' [roywspencer@hotmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** RE: ch 4 revisions  
**Attachments:** ~WRD0005.jpg

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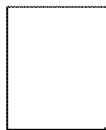
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**Subject:** Re: ch 4 revisions  
**Attachments:** S02 Hall and Manabe.pdf

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<http://www.cfanclimate.net>

## The Role of Water Vapor Feedback in Unperturbed Climate Variability and Global Warming

ALEX HALL\*

*Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, New Jersey*

SYUKURO MANABE<sup>†</sup>

*Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey*

(Manuscript received 6 November 1997, in final form 9 June 1998)

### ABSTRACT

To understand the role of water vapor feedback in unperturbed surface temperature variability, a version of the Geophysical Fluid Dynamics Laboratory coupled ocean–atmosphere model is integrated for 1000 yr in two configurations, one with water vapor feedback and one without. For all spatial scales, the model with water vapor feedback has more low-frequency (timescale  $\geq 2$  yr) surface temperature variability than the one without. Thus water vapor feedback is positive in the context of the model's unperturbed variability. In addition, water vapor feedback is more effective the longer the timescale of the surface temperature anomaly and the larger its spatial scale.

To understand the role of water vapor feedback in global warming, two 500-yr integrations were also performed in which  $\text{CO}_2$  was doubled in both model configurations. The final surface global warming in the model with water vapor feedback is  $3.38^\circ\text{C}$ , while in the one without it is only  $1.05^\circ\text{C}$ . However, the model's water vapor feedback has a larger impact on surface warming in response to a doubling of  $\text{CO}_2$  than it does on internally generated, low-frequency, global-mean surface temperature anomalies. Water vapor feedback's strength therefore depends on the type of temperature anomaly it affects. The authors found that the degree to which a surface temperature anomaly penetrates into the troposphere is a critical factor in determining the effectiveness of its associated water vapor feedback. The more the anomaly penetrates, the stronger the feedback. It is also shown that the apparent impact of water vapor feedback is altered by other feedback mechanisms, such as albedo and cloud feedback. The sensitivity of the results to this fact is examined.

Finally, the authors compare the local and global-mean surface temperature time series from both unperturbed variability experiments to the observed record. The experiment without water vapor feedback does not have enough global-scale variability to reproduce the magnitude of the variability in the observed global-mean record, whether or not one removes the warming trend observed over the past century. In contrast, the amount of variability in the experiment with water vapor feedback is comparable to that of the global-mean record, provided the observed warming trend is removed. Thus, the authors are unable to simulate the observed levels of variability without water vapor feedback.

### 1. Introduction

The precise amount of warming that would take place for a given increase in greenhouse gases in the atmosphere remains an unknown quantity. According to the latest Intergovernmental Panel on Climate Change as-

essment, the likely equilibrium global-mean temperature response to a doubling of  $\text{CO}_2$  ranges from  $1.5^\circ$  to  $4.5^\circ\text{C}$  (Intergovernmental Panel on Climate Change 1996). The source of this uncertainty is our inability to quantify the role of feedback mechanisms in the climate system, including water vapor, cloud, lapse rate, and albedo feedback. Water vapor feedback, the subject of this study, has long been thought to be a positive feedback mechanism (see, e.g., Manabe and Wetherald 1967). This is due to the dependence of the saturation water vapor mixing ratio on temperature, as predicted by the Clausius–Clapeyron equation. Thus a  $\text{CO}_2$ -induced warming of the surface–troposphere system will lead to a water vapor increase in the atmosphere. Since water vapor is itself a greenhouse gas, this increase will reduce the longwave radiative damping of the temper-

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\* Current affiliation: Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York.

<sup>†</sup> Current affiliation: Earth Frontier Research System, Tokyo, Japan.

---

Corresponding author address: Alex Hall, Lamont-Doherty Earth Observatory of Columbia University, Oceanography Bldg., Room 103, P.O. Box 1000, 61 Route 9W, Palisades, NY 10964-8000.  
E-mail: alexhall@rosie.ldeo.columbia.edu

ature anomaly, making the warming larger than it would be otherwise. While there is a consensus that water vapor feedback is positive in the context of global warming, it remains unclear exactly how strong the effect is (Dickinson et al. 1996). Large uncertainties also exist regarding the magnitude (and sign, in the case of cloud feedback) of the other feedback mechanisms.

If a particular feedback mechanism is an important factor in greenhouse-gas-induced climate change, it ought to play an important role in unperturbed variability as well. To take the example of water vapor feedback, suppose an internally generated forcing, such as a change in net cloud cover associated with atmospheric disturbances, were to induce a warm anomaly in the surface–troposphere system. A resulting increase in atmospheric water vapor and hence greenhouse trapping of outgoing radiation would reduce the radiative damping of the anomaly. This, in turn, will increase its magnitude. Similarly, since colder air holds less water vapor, a cold surface–troposphere anomaly ought to be associated with reduced water vapor mixing ratios. This would enhance the outgoing longwave radiation, making the anomaly cooler than if there were no decrease in water vapor. Thus while water vapor feedback plays no role in generating the temperature anomalies themselves, whether externally forced or internally generated, it ought to have a significant impact on their magnitude. In this way, water vapor feedback can be said to “enhance” or “amplify” temperature anomalies of the surface–troposphere system.

Despite its importance to the sensitivity and variability of climate, a comprehensive picture of water vapor feedback’s impact on both externally forced and internally generated climate variations is lacking. For example, it is completely unknown whether water vapor feedback amplifies an externally forced climate fluctuation, such as that arising from an increase in greenhouse gases, to the same degree that it amplifies internally generated climate variations. If this were the case, it would obviously be of enormous importance, because water vapor feedback’s contribution to the sensitivity of the climate to a greenhouse gas increase could be estimated from unperturbed variability alone. In addition, the impact of water vapor feedback on unperturbed temperature variability is itself very poorly characterized: does water vapor feedback’s strength depend on the timescale of an internally generated temperature anomaly? On its spatial scale? Addressing these fundamental issues using a coupled ocean–atmosphere model is the goal of this study. In so doing, we aim to develop a comprehensive, albeit qualitative, picture of the basic operation of water vapor feedback.

These issues have never been directly addressed before because they are impossible to study using the observed record alone. It has only been within the past few years that satellite data measuring water vapor content, outgoing longwave radiation, and surface temperature have become available. Even assuming this dataset

is accurate, it is still too short to give reliable statistics on many aspects of water vapor feedback and is likely to remain so for quite some time. A numerical model of the climate, on the other hand, provides long time series with global coverage that are reliable in a statistical sense. Moreover, a numerical model is a very flexible scientific tool because any physical mechanism it includes may be removed from the simulation and the effect of the mechanism may be diagnosed. In this study, we disable the water vapor feedback of a coupled ocean–atmosphere model by fixing the water vapor mixing ratios to their climatological mean values in the longwave portion of the model’s radiative transfer subroutine. Thus anomalies in water vapor predicted by the model’s hydrological component are not taken into account in the longwave radiative transfer calculation. In this way, if atmospheric water vapor increases due to a warm surface temperature anomaly, for example, that change in water vapor will not result in any increased greenhouse trapping. In this study, we also employ a model configuration where water vapor is allowed to interact with longwave radiation, as the model was originally designed. By comparing the variability that results from unperturbed long-term integrations of the two model configurations with and without water vapor feedback (referred to hereafter as the control and fixed  $H_2O$  configurations), we can measure directly the impact of water vapor feedback on the model’s unperturbed variability in a way that is not feasible through analysis of the observed record. Unlike the real world, we can also manipulate at will the concentrations of greenhouse gases in a numerical model. Thus we can measure the warming that results in the control and fixed  $H_2O$  configurations when  $CO_2$  is gradually increased and then held fixed at twice its original value. This, in turn, allows us to compare the role of water vapor feedback in greenhouse-gas-induced global warming to its role in unperturbed variability. Since the suppression of unperturbed variability and the reduction of global warming in the fixed  $H_2O$  model are attributable to the same physical mechanism, our approach is self-consistent.

The presentation of this study is structured as follows. First, we give a detailed description of the numerical model (section 2) and the experimental technique (section 3) used in these simulations. In section 4, the analysis of water vapor feedback’s role in unperturbed variability is presented. The main focus in this section is the dependence of water vapor feedback’s strength on the time and spatial scale of the temperature anomaly it affects. In section 5, the results of the global warming experiments are given and comparisons are made between the contributions of water vapor feedback to climate sensitivity in the unperturbed variability and global warming contexts. Then, in section 6, we examine the way in which other feedback mechanisms, such as albedo and cloud feedback, alter the apparent impact of water vapor feedback in both the unperturbed variability and global warming contexts. Section 7a outlines the



main conclusions of the analysis. Finally, in section 7b, we place the fixed  $H_2O$  and control simulations in the context of the real climate. By comparing the unperturbed temperature variability of the fixed  $H_2O$  and control simulations to the observed temperature record, we assess whether the model's water vapor feedback is necessary to simulate the observed levels of variability.

## 2. Model structure and time integration

The most important features of this model are described in some detail in Manabe et al. (1991). It consists of a general circulation model of the world ocean coupled to an atmospheric general circulation model through exchange of heat, water, and momentum. The model includes those features of the earth's geography that its resolution permits. It also has a seasonal cycle of insolation, although the diurnal cycle is not included.

The variables of the atmospheric component are represented in the horizontal by a series of spherical harmonics and corresponding gridpoint values. Fifteen zonal waves and associated Legendre functions are included in the integration (Orszag 1970; Gordon and Stern 1982). When the atmospheric data is transformed from spectral space to real space for the purposes of analysis, this resolution results in a grid box size of about  $4.5^\circ$  lat  $\times$   $7.5^\circ$  long. In the vertical, finite differencing is used at nine unevenly spaced levels. The radiative transfer calculation includes the effects of clouds, water vapor, carbon dioxide, and ozone on both incoming and outgoing radiation. The sky is overcast whenever the relative humidity exceeds a critical level; otherwise clear sky is predicted. While the distribution of water vapor is predicted by the model, carbon dioxide concentration is taken to be constant, except in the global warming experiments described below. Ozone is specified as a function of latitude, height, and time of year, following observations given by Hering and Borden (1965). At the land surface, the model computes budgets of snow, water, and heat. Soil moisture is parameterized using a "bucket" model: At every land surface grid point, water is accumulated through precipitation and depleted through evaporation in a bucket whose surface area is the same as the grid box. At any given time, if the water depth in the bucket exceeds 15 cm, runoff is predicted. Otherwise, soil moisture is given by the depth of the water in the bucket.

The finite-difference oceanic component, with a horizontal resolution of  $4.5^\circ$  lat  $\times$   $3.75^\circ$  long and 12 vertical levels, uses the modular ocean model (MOM) code described in Pacanowski et al. (1991). This particular version of MOM is based, in turn, on a model described by Bryan and Lewis (1979). In addition to horizontal and vertical background subgrid-scale mixing, the model has isopycnal mixing as discussed by Redi (1982) and Tziperman and Bryan (1993). Convection occurs whenever the vertical stratification becomes unstable.

Sea ice is predicted using a free drift model developed by Bryan (1969).

At the beginning of time integration, the model's atmosphere and ocean are both individually in equilibrium with realistic seasonal and geographical distributions of sea surface temperature, sea surface salinity, and sea ice. However, as the integration proceeds, the model's climate usually drifts toward its own, less realistic, equilibrium state. This distorts the simulated variability that this study seeks to diagnose. Moreover, it would be difficult to interpret a global warming experiment where the radiative forcing perturbation is applied to a basic-state climate that is already diverging significantly from the present-day equilibrium state. Therefore, to minimize the climate drift, the fluxes of heat and water obtained from the atmospheric component of the coupled model are modified by given amounts before they are imposed upon the ocean surface. While these adjustments vary seasonally and geographically, they do not vary from year to year. Therefore, they are not correlated to the transient sea surface temperature and salinity anomalies that develop over the course of the coupled integration. Thus flux adjustment is unlikely either to amplify or damp these anomalies in a systematic way. Although the adjustments do not eliminate the shortcomings of the model (Marotzke and Stone 1995), they do prevent rapid drift of the simulated climate from realistic initial conditions. Using this flux adjustment technique, only very small trends associated with climate drift remain. For example, over the entire period of the 1000-yr integration, the fixed  $H_2O$  run exhibits a cooling trend of  $0.009^\circ\text{C century}^{-1}$  in global-mean surface temperature. A trend of a similar magnitude exists in the 1000-yr control run ( $0.035^\circ\text{C century}^{-1}$ ). For the purposes of the analysis of the model's unperturbed variability, all such linear trends were first removed from the data.

## 3. Experimental design

As noted in section 1, this model was integrated in two configurations to test the effects of water vapor feedback. In both cases, water vapor is variable in the hydrologic component of the model, meaning that simulated clouds and precipitation are based on humidity values predicted by the model. In the fixed  $H_2O$  configuration, however, water vapor mixing ratios at all grid points and all nine vertical levels are fixed to their climatological mean, seasonally varying values in the longwave portion of the radiative transfer subroutine. In the control configuration, on the other hand, the water vapor values predicted by the hydrologic component are passed to the longwave subroutine. The mean water vapor field used in the fixed  $H_2O$  experiments was calculated in the following way. First, integrating only the atmospheric component of the coupled model, and using seasonally varying, climatological sea surface temperatures and sea ice as a lower boundary condition, the

daily mean values of the entire water vapor field were saved away for 50 yr. Then the values corresponding to any given day of the annual cycle were averaged over all 50 yr of the integration, providing a mean water vapor field for every day of the year. These mean values were supplied to the coupled model's longwave radiative transfer subroutine as the coupled integration proceeded through each day of the year.

It should be emphasized that since water vapor was fixed only in the longwave radiative transfer subroutine of the fixed H<sub>2</sub>O configuration, any feedback effects due to water vapor's interaction with solar radiation are included in both configurations. The aspect of water vapor feedback relating to solar radiation is therefore not a subject of this study. However, it also constitutes a positive feedback mechanism, since water vapor absorbs solar radiation. For example, a warm surface-troposphere temperature anomaly will increase the amount of water vapor in the atmosphere and enhance the absorption of solar radiation there, thereby amplifying the warm anomaly. If we had fixed water vapor in the solar radiative transfer subroutine as well as the long wave, the fixed H<sub>2</sub>O experiment would have had even less positive feedback and therefore less unperturbed variability and a smaller response to a doubling of CO<sub>2</sub>. However, this effect is quite small; the impact of the shortwave component of water vapor feedback, though positive, is approximately an order of magnitude smaller than the longwave component (Ramanathan and Coakley 1978). For the sake of simplicity, the term "water vapor feedback" refers only to the longwave feedback effects of water vapor throughout this article.

The model was integrated for 1000 yr in each configuration. These integrations will be referred to as the unperturbed variability experiments. The last 800 yr of these time series were used to analyze the effects of water vapor feedback on the model's internally generated variability. The global warming experiments were initialized using the same initial conditions as the two unperturbed variability experiments. Integrating the model in both configurations, CO<sub>2</sub> was then increased at a rate of 1% per year until its concentration doubled, around year 70. Thereafter it was fixed at the doubled value (720 ppm) for the remainder of the 500-yr-long experiments.

#### 4. Spatial and timescale dependence of water vapor feedback in unperturbed variability

As mentioned in section 1, one goal of this study is to understand the spatial and timescale dependence of water vapor feedback in the unperturbed temperature variability of the surface-troposphere system. Does the contribution of water vapor feedback depend upon the geographical extent of the temperature anomaly? Does it depend on how long the anomaly persists? To simplify the analysis, we selected a single variable—surface temperature—that would be broadly representative of the

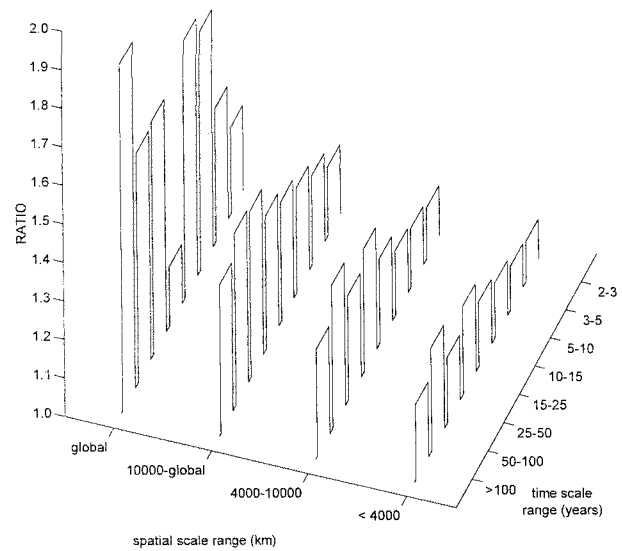


FIG. 1. The ratio control/fixed H<sub>2</sub>O of the standard deviation of surface temperature anomalies, indicated by the heights of the bars, as a function of spatial scale and timescale. The ranges of time- and spatial scales selected for the analysis are shown in the figure. The spatial filtering required for the calculation of these ratios was performed in the following way. First, spatial filtering was carried out on the model's 48 × 40 grid using a Hamming digital filter in the zonal direction and a Fourier filter in the meridional direction. To select the same spatial scales at all latitudes, the digital filter varied by latitude row, taking into account the reduction in the length of a latitude circle as higher latitudes are chosen. Applying the filters in both the zonal and meridional directions to global fields of surface temperature anomalies, a new time series was produced at each grid point.

impact of water vapor feedback on these anomalies. Thus to answer these questions we compare the surface temperature variability in the fixed H<sub>2</sub>O 1000-yr run to the control 1000-yr run on various spatial scales and timescales. Since water vapor feedback is present in the control case but absent in the fixed H<sub>2</sub>O case, differences in variability may be ascribed to water vapor feedback. Using the following technique, it was possible to focus on any given range of spatial scales and timescales. First, the temperature anomalies of the spatial scales of interest, from 4000 to 10 000 km, for example, were selected by applying the appropriate filter in the zonal and meridional directions to each field of annual-mean temperature anomalies. Similarly, the variability corresponding to a given range of timescales, from 10 to 15 yr, for example, was extracted by bandpass filtering the resulting time series at each grid point. After applying this series of filters to both the control and fixed H<sub>2</sub>O time series, the variability of the filtered control time series was compared to its fixed H<sub>2</sub>O counterpart by taking the ratio of the control to fixed H<sub>2</sub>O standard deviations at each grid point. Figure 1 depicts graphically how the global mean of this ratio changes as various spatial scales and timescales are selected. In addition, to study the role of water vapor feedback on the largest (i.e., global) spatial scale, global-mean surface

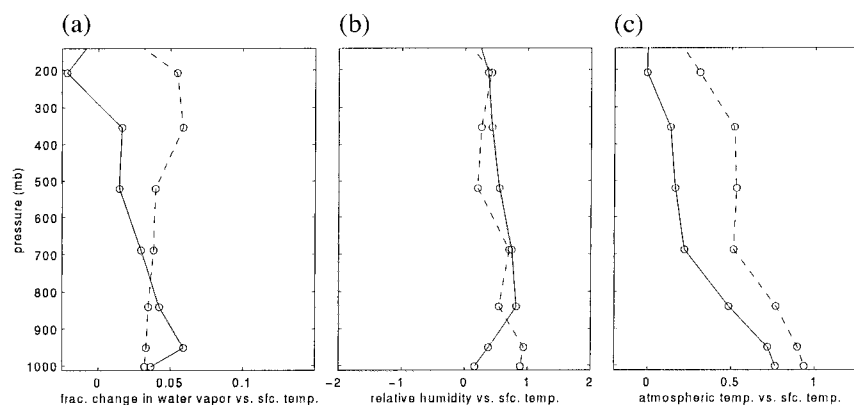


FIG. 2. The regressions between (a) fractional changes in water vapor mixing ratios and surface temperature ( $^{\circ}\text{C}$ ), (b) relative humidity (%) and surface temperature, and (c) troposphere temperature and surface temperature in the seven lowest levels of the model (142–1013 hPa) for local (solid) and global (dashed) cases.

temperature time series were calculated for both runs. These two time series were bandpass filtered at various timescales and the variability in the control run was compared to the fixed  $\text{H}_2\text{O}$  run by taking the ratio of the two standard deviations. These ratios are also plotted in Fig. 1 for comparison with smaller spatial scales.

Two conclusions may be drawn from this figure. First, the ratio is greater than one for all time- and spatial scales, implying that there is more surface temperature variability in the control run than in its fixed  $\text{H}_2\text{O}$  counterpart on all time and spatial scales. Thus water vapor feedback is a positive feedback mechanism that enhances the internally generated surface temperature variability of this model. Second, the ratio increases as larger spatial scales and longer timescales are selected. For example, in the case of the small spatial-scale anomalies (spatial scale  $< 4000$  km), the ratio increases from 1.10 for the 2–3-yr timescale to 1.19 for the longest timescales ( $> 100$  yr). More importantly, the ratio generally increases very dramatically the larger the spatial scale in question. For example, on the 5–10-yr timescale, the ratio increases from 1.14 for anomalies smaller in spatial scale than 4000 km, to 1.62 for global-mean anomalies. On the longest timescales ( $> 100$  yr) the ratio increases from 1.19 for small-scale anomalies to 1.90 in the global-mean case.

Since water vapor feedback is a positive feedback mechanism in unperturbed variability, tropospheric absolute humidity must increase (decrease) as surface temperature increases (decreases). This relationship results from the fact that the saturation mixing ratio of water vapor increases exponentially with temperature. Thus a temperature anomaly in the surface–troposphere system is associated with an anomaly of the same sign in the water-vapor-holding capacity of the atmosphere. If condensation in the troposphere and evaporation from the surface act to keep relative humidity approximately constant throughout the troposphere, then absolute humidity levels will fluctuate in phase with surface–troposphere

temperature. By testing this reasoning, we aim to explain, at least in part, the most important result from Fig. 1: that water vapor feedback is more effective at large spatial scales than small.

The argument outlined above depends on the relationships between three tropospheric variables and surface temperature: absolute humidity, relative humidity, and air temperature. Accordingly, Fig. 2 shows the regressions at every level of the model's troposphere between these variables and surface temperature. All calculations are based on annual-mean data from the control unperturbed variability experiment. To clarify how each of these quantities responds to large- and small-scale surface temperature anomalies, the regressions were calculated for two cases. In all three panels, the regressions between global-mean atmospheric variables and global-mean surface temperature are shown with a dashed line, while the global means of the local regressions, calculated separately at every grid point, are shown with a solid line. Thus the dashed lines represent the relationships between surface temperature and absolute humidity, relative humidity, and air temperature, and on the largest (global) spatial scale. On the other hand, the solid lines show how, on average, local fluctuations in these quantities relate to changes in local surface temperature. Of course, local anomalies include contributions from all spatial scales larger than a grid box, including the global scale. However, the variability at a single grid point is overwhelmingly dominated by fluctuations smaller in spatial scale than the global scale. For example, in the control unperturbed variability experiment, the global-mean standard deviation of local surface temperature is about  $0.74^{\circ}\text{C}$ , whereas the standard deviation of global-mean surface temperature is only about  $0.13^{\circ}\text{C}$ . Since the magnitude of a typical global anomaly is so much smaller than the magnitude of a typical local anomaly, fluctuations smaller in spatial scale than the global scale must be responsible for most local variability. We may therefore consider the regres-

sions shown by solid lines to represent relationships between atmospheric variables and surface temperature at spatial scales much smaller than the global scale.

We begin the discussion of these results by focusing on Fig. 2a. Regressions were calculated using fractional changes in absolute humidity, rather than absolute humidity itself, to focus directly on the impact of water vapor fluctuations on the radiative properties of the atmosphere. Since longwave absorptivity due to water vapor is approximately proportional to the logarithm of the water vapor mixing ratio in the troposphere, fractional changes in water vapor are roughly proportional to changes in atmospheric absorptivity due to water vapor. Figure 2a illustrates water vapor feedback's greater impact on large spatial scales than small in terms of this relationship. In the lower troposphere, the strength of the global-scale relationship between absorptivity due to water vapor and surface temperature is not significantly different from that of the local anomalies. However, in the mid- to upper troposphere, the situation is very different. Here, the global-scale relationship is much stronger than its local counterpart. Because of the proximity to the top of the atmosphere, changes in absorptivity here probably have a larger effect on the atmosphere's greenhouse effect than if a similar change were to occur in the lower troposphere. In any case, when the entire troposphere is considered, a given global-mean temperature anomaly induces a larger fractional increase in water vapor in the air column above than a typical local anomaly of the same magnitude.

But why are the fractional changes in water vapor per degree change in surface temperature larger in the global than the local case? Figure 2b shows that relative humidity changes very little as surface temperature fluctuates; the regressions are nearly zero throughout the troposphere for both local and the global cases. This indicates that neither local nor global surface temperature anomalies are associated in any systematic way with anomalies in relative humidity in the troposphere. The differing relationships between absolute humidity and surface temperature must therefore be explained by differences in the relationships between tropospheric temperature and surface temperature, as illustrated in the right panel. This panel shows that global-scale surface temperature anomalies penetrate much more deeply into the troposphere than their local counterparts. This is most apparent in the upper troposphere, where the regressions between atmospheric temperature and surface temperature in the global case are nearly four times as large as in the local case. Given that the same surface temperature anomalies induce virtually no change in relative humidity, this implies a larger change in absolute humidity in the global case.

The results presented in Fig. 2 explain how water vapor feedback's contribution to the radiative damping of temperature anomalies depends on their spatial scale. However, temperature anomalies of the surface-troposphere system may also be damped by horizontal ex-

change of sensible heat within the atmosphere itself. The effectiveness of this process also depends on the anomalies' spatial scale. For example, a small-scale temperature anomaly would be very effectively diffused into surrounding regions by horizontal advective heat exchange. Clearly, this diffusive damping of temperature anomalies is less effective the larger the anomaly's spatial scale. At the global scale, of course, it is nonexistent. Since water vapor feedback operates exclusively on the radiative component of the damping, the impact of water vapor feedback on small spatial scales may be smaller simply because the relative contribution of radiative damping to the total damping is smaller. This constitutes another explanation for the spatial scale dependence of the ratio plotted in Fig. 1. It should also be pointed out that advective processes in the atmosphere are also the main reason why the regressions of local atmospheric temperature and surface temperature, shown in Fig. 2c, are smaller than their global-mean counterparts. This, in turn, is responsible for the weaker water vapor feedback in the case of the local anomalies. Thus advection not only contributes heavily to the damping of small-scale surface temperature anomalies, obscuring the effects of water vapor feedback, but it also weakens water vapor feedback itself.

Temperature anomalies are damped by evaporative fluxes across the air-surface interface as well. This process is also likely to be more effective at small spatial scales due to the increasing effects of advection as spatial scales decrease. For example, while a warm global-scale anomaly may be associated with enhanced evaporation at the surface, this latent heat must ultimately be released in the atmosphere. This would result in an enhancement of the warm anomaly in the troposphere, which must in turn warm the surface through enhanced radiative and sensible heat fluxes, counteracting the cooling effect of the initial evaporative flux. The net damping effect of the evaporative flux on the global-mean surface-troposphere temperature anomaly is therefore limited. A small-scale warm anomaly would also result in enhanced evaporation. Although this latent heat must be released somewhere in the atmosphere, it may be released at a different location, resulting in an export of heat out of the region of the anomaly. In this case, the effect of the initial evaporative flux at the surface would be to damp the entire surface-troposphere anomaly. Thus evaporative damping may also obscure the effects of water vapor feedback at small scales by decreasing the relative contribution of radiative processes to the total damping.

We have seen how and why water vapor feedback affects internally generated surface temperature variability on various spatial scales. We now verify that water vapor feedback actually alters the top-of-the-atmosphere, longwave radiative damping of these anomalies in a manner consistent with its impact on their variability. The first row of the first column of Table 1 shows the regression between global-mean, clear-sky

TABLE 1. The regressions between global-mean clear-sky outgoing longwave radiation and global-mean surface temperature (first row) and the global-mean of the regressions between local clear-sky outgoing longwave and local surface temperature (second row). The third column shows the difference in the regressions between the control and fixed  $H_2O$  cases.

|                            | Control | Fixed $H_2O$ | Difference |
|----------------------------|---------|--------------|------------|
| Global anomalies           |         |              |            |
| $W\ m^2\ (^{\circ}C)^{-1}$ | 1.97    | 2.69         | 0.72       |
| Local anomalies            |         |              |            |
| $W\ m^2\ (^{\circ}C)^{-1}$ | 1.42    | 1.92         | 0.50       |

outgoing longwave radiation and global-mean surface temperature for the control unperturbed variability experiment. Immediately below is the global-mean of the regressions between local clear-sky outgoing longwave and local surface temperature. These two values represent the change in the clear-sky longwave flux at the top of the atmosphere per unit change in surface temperature on both the local and the global scale. This is a measure of the strength of the radiative damping of surface temperature. By examining clear-sky fluxes, we eliminate the effects of cloud feedback. The second column presents the results of the same calculations for the fixed  $H_2O$  experiment. Finally, the third column shows the difference in the regressions between the control and fixed  $H_2O$  cases. In both the local and the global cases, the regressions are larger for the experiment without water vapor feedback; the presence of water vapor feedback in the control experiment reduces the longwave damping of both local and global temperature anomalies. In the global case, water vapor feedback reduces the damping by  $0.72\ W\ m^{-2}\ ^{\circ}C^{-1}$ , the difference between the two regressions, whereas in the local case, the damping is reduced by  $0.50\ W\ m^{-2}\ ^{\circ}C^{-1}$ . The reduction is larger for the global-mean case, which is consistent with the observation that water vapor feedback is more effective the larger the spatial scale.

### 5. Water vapor feedback and global warming

We wish to examine the role of water vapor feedback in global warming as well as unperturbed variability. As described in section 3, global warming experiments were performed integrating the model in both configurations. Carbon dioxide was increased starting at the beginning of the two integrations a rate of  $1\%\ yr^{-1}$  until its concentration doubled around year 70. Thereafter it was fixed at its doubled value (720 ppm). Just as in the analysis of unperturbed variability presented in section 4, we analyzed surface temperature to diagnose the climate change in the two experiments. Figure 3 shows the 500-yr annual-mean time series of the global-mean surface temperature change in these integrations relative to the unperturbed variability experiments, where  $CO_2$  is fixed at 360 ppm. In both the fixed  $H_2O$  and control cases, there is a steady warming for the first 70 yr. After year 70, the warming continues but at a much slower

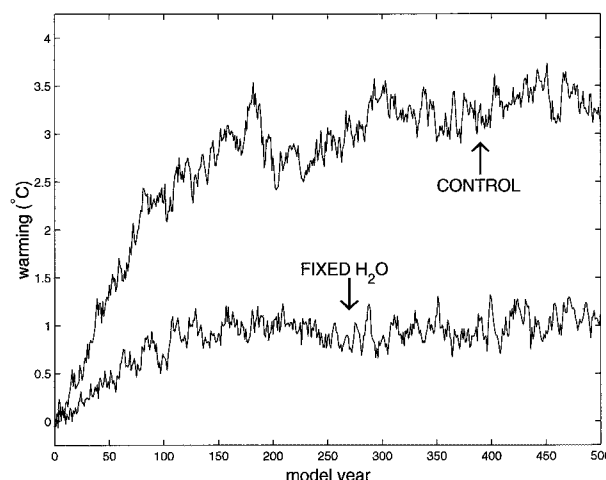


FIG. 3. The 500-yr annual-mean time series of the global-mean surface temperature change in the integrations where  $CO_2$  is doubled to 720 ppm relative to the unperturbed variability experiments, where  $CO_2$  is fixed at 360 ppm.

rate for the remainder of the experiments. If the integrations were continued beyond year 500, both climates would likely continue to change slowly for several centuries in response to the new  $CO_2$  value. However, enough of the climate change has occurred by this point that we may consider the climates toward the end of these integrations to be broadly representative of their equilibrium response to the increase in  $CO_2$ . It is clear from the figure that the magnitude of the warming is much larger in the model that contains water vapor feedback than the model that does not: The warming averaged over the last century of the integrations is  $3.38^{\circ}C$  in the control case, while it is only  $1.05^{\circ}C$  in the fixed  $H_2O$  case.

These results demonstrate that water vapor feedback is positive in the global warming case just as it is positive in the context of unperturbed variability. However, the amount by which water vapor feedback amplifies global warming is larger than the amount by which it amplifies the magnitude of a typical internally generated surface temperature anomaly. Since standard deviation is a measure of the magnitude of a typical anomaly, this may readily be seen by comparing the ratio (control/fixed  $H_2O$ ) of standard deviation of surface temperature to the ratio of the warming. If water vapor feedback is equally effective in both, then the ratios should be identical. Since  $CO_2$ -induced warming occurs on a global scale, and because of the spatial-scale dependence of water vapor feedback documented in section 4, we compare the warming ratio to the ratio of standard deviation of global-scale temperature fluctuations. The warming ratio is  $3.38^{\circ}C/1.05^{\circ}C = 3.2$ . However, the ratio of standard deviation of global-mean, annual-mean surface temperature is 1.53. Thus water vapor feedback is more than twice as effective in enhancing global warming as

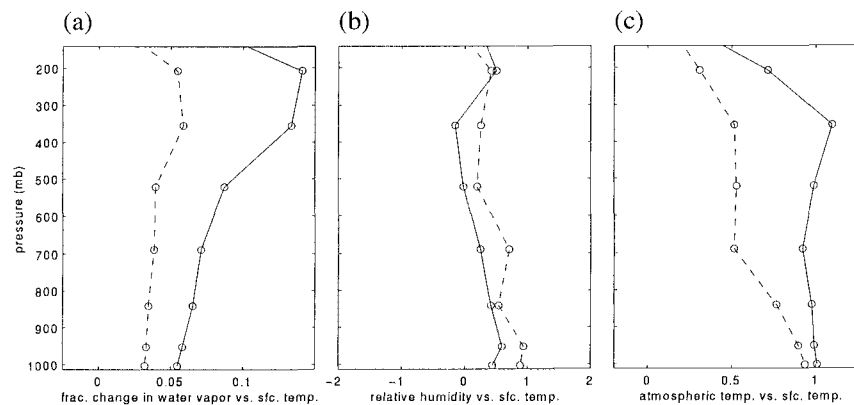


FIG. 4. As in Fig. 2, (a) the relationships between fractional changes in water vapor and surface temperature ( $^{\circ}\text{C}$ ), (b) the relationships between relative humidity (%) and surface temperature, and (c) the relationships between tropospheric temperature ( $^{\circ}\text{C}$ ) and surface temperature. In all three panels, the solid lines indicate the relationships between atmospheric variables and surface temperature for the global warming case. The dashed lines show the regressions between global-mean values and global-mean surface temperature from the control unperturbed variability experiment. Note that Fig. 4 has the same aspect ratio and axes as Fig. 2.

it is in amplifying internally generated, global-mean temperature anomalies.

In section 4 we explained why the effectiveness of water vapor feedback depends on spatial scale by examining the relationships between surface temperature on the one hand and fractional changes in absolute humidity, relative humidity, and tropospheric temperature on the other. Using identical methods, we now explain why water vapor feedback is so much more effective in global warming than unperturbed variability. In direct analogy to Fig. 2, Fig. 4 shows the relationships between fractional changes in water vapor and surface temperature, relative humidity and surface temperature, and tropospheric temperature and surface temperature. All of the dashed curves indicate regressions between global-mean, annual-mean values from the control unperturbed variability experiment. They are therefore identical to the dashed curves in Fig. 2. The solid lines, while not regressions, indicate the analogous relationships between atmospheric variables and surface temperature for the global warming case. In the case of atmospheric temperature (right panel), these values were calculated by subtracting the global-mean tropospheric temperatures averaged over years 401–500 of the control unperturbed variability experiment from the global-mean tropospheric temperatures averaged over years 401–500 of the control global warming experiment. The differences were then divided by the difference in global-mean surface temperature averaged over the same time period. The resulting ratios therefore represent the warming that takes place in the troposphere per degree surface temperature warming, just as the regressions represented by the dashed lines indicate the tropospheric temperature changes that take place per degree surface temperature fluctuation. The relationships between relative humidity and surface temperature (middle panel)

were calculated in a similar fashion. The values indicated by the solid line in the left panel were calculated by first taking the difference between the global-mean mixing ratios averaged over years 401–500 of the control global warming and unperturbed variability experiments and dividing by the average mixing ratios from the unperturbed variability experiment. Finally, these fractional changes in water vapor were divided by the difference in global-mean surface temperature between the two experiments.

First, we compare the relationships between the fractional changes in water vapor and surface temperature for global-scale unperturbed variability and the global warming, shown on the left in Fig. 4. As described in section 4, this is approximately equivalent to analyzing the relationship between atmospheric absorptivity due to water vapor and surface temperature. At all levels of the troposphere, there is a strong positive relationship between fractional changes in water vapor and surface temperature for both the unperturbed variability and global warming cases. However, for a given change in surface temperature, a much larger fractional change in water vapor occurs in the global warming case. Although this is true at all levels of the troposphere, it is most apparent in the upper troposphere, where changes in absorptivity probably have a larger effect on the atmosphere's greenhouse effect than if a similar change were to occur in the lower troposphere. This evidence is consistent with the fact that water vapor feedback is more effective in enhancing global warming than in amplifying internally generated, global-mean anomalies.

We have already established that, throughout the troposphere, there is no systematic relationship between internally generated, global-mean relative humidity and surface temperature anomalies. The middle panel of Fig.

4 shows that relative humidity also changes very little as the surface warms in response to increased  $\text{CO}_2$ . There is a very small increase of a few tenths of a percent per degree warming in the lower troposphere, while in the mid- to upper troposphere, the relationship falls off nearly to zero. Thus in both the unperturbed variability and global warming cases, surface temperature anomalies have very little effect on tropospheric relative humidity.

Given that the relative humidity anomalies associated with surface temperature anomalies are small in both unperturbed variability and global warming cases, the degree to which a surface temperature anomaly penetrates the troposphere must be a critical factor in determining the strength of the water vapor feedback. We now examine both the vertical structures of the warming in the global warming experiment and temperature anomalies in the unperturbed variability experiment, shown in Fig. 4c. In both cases, there is a strong relationship between temperature anomalies aloft and temperature anomalies at the surface. However, the relationship is much stronger in the global warming case, where the warming is nearly uniform throughout the entire troposphere. In the unperturbed variability case, on the other hand, the regression between tropospheric temperature and surface temperature decreases from almost 1 near the surface to about 0.3 at 200 hPa. Internally generated, global-mean temperature anomalies do not penetrate as effectively into the troposphere as warming induced by a doubling of  $\text{CO}_2$ . Thus for a  $\text{CO}_2$ -induced warming and an internally generated warm anomaly of the same magnitude, the fact that relative humidity changes very little in both cases implies a much larger increase in upper-tropospheric water vapor mixing ratios in the global warming case than the unperturbed variability case. This implies a stronger water vapor feedback to global warming.

Since the degree to which a surface temperature anomaly penetrates the troposphere is such a critical factor in determining the strength of its associated water vapor feedback, it is desirable to gain an understanding of why internally generated, global-mean temperature anomalies do not penetrate as effectively into the troposphere as the warming induced by a doubling of  $\text{CO}_2$ . To shed light on this issue, we examined the characteristic horizontal structure of both global-scale unperturbed temperature variability and global warming at every level of the model's troposphere. To see how the characteristic horizontal structure of internally generated, global-mean temperature anomalies changes with height, we calculated regressions between local and global-mean temperature at each level of the troposphere using annual-mean data from the control unperturbed variability experiment. To simplify the presentation of these results, we then computed the mass-weighted average of these regressions over two layers of the troposphere, one corresponding to the lower troposphere (770–1013 hPa), and the other corresponding

to the mid- and upper troposphere (273–770 hPa). The geographical distribution of these regressions for both layers is shown in Fig. 5. The patterns for both layers are very similar to the patterns for their constituent levels and are therefore broadly representative of the change with height in the horizontal structure of global-mean temperature anomalies. We also performed an analogous calculation for the global warming case. We first computed the warming due to a doubling of  $\text{CO}_2$  at each grid point and each vertical level of the troposphere by taking the difference in temperature between the control global warming and unperturbed variability experiments averaged over the fifth century of both integrations. Then, at each vertical level, we divided these values by the global-mean warming at that level. Finally, we calculated the mass-weighted average of these ratios over the lower (770–1013 hPa) and mid- to upper (273–770 hPa) troposphere, as before. The geographical distribution of these values is shown in Fig. 6.

We begin the discussion of these calculations by examining the unperturbed variability case. Figure 5b reveals that global-mean temperatures in the lower troposphere are dominated by contributions from midlatitude land locations, the high latitudes of the Southern Hemisphere, and a region stretching from the equatorial to the southeastern tropical Pacific. Thus when global-mean lower-tropospheric temperature is anomalously warm, these regions also tend to be warm. The regression pattern for surface temperature (not shown) is very similar. At the same time, Fig. 5a shows that when global-mean temperatures in the upper troposphere are warm, temperatures in other regions—mainly a wide band stretching across nearly the entire world from 30°N to 30°S—tend to be warm. Thus the regions contributing most to global-mean variability shift markedly as one goes from the surface and lower troposphere to the mid- and upper troposphere. Temperature variability in the regions that dominate the mid- and upper-tropospheric global-mean variability is most likely only weakly related to the variability in the distant regions that dominate the global-mean variability at the surface and in the lower troposphere. This explains the substantial decrease with height in the regression between global-mean tropospheric temperature and surface temperature seen in the dashed line of Fig. 4c.

A very different picture emerges from the global warming case. Figure 6b shows that, in the lower troposphere, warming is larger than the global-mean value in the mid- to high latitudes of both hemispheres, while it is less than the global-mean value in much of the midlatitudes and Tropics. The ratio pattern at the surface (not shown) is very similar. Figure 6a also reveals a similar pattern for the mid- and upper troposphere, although the equator-to-pole contrast in the ratio is somewhat smaller. Thus where warming is large at the surface and in the lower troposphere, it is also large in the mid- and upper troposphere. This confirms that the uniform global-mean tropospheric warming seen in the solid line

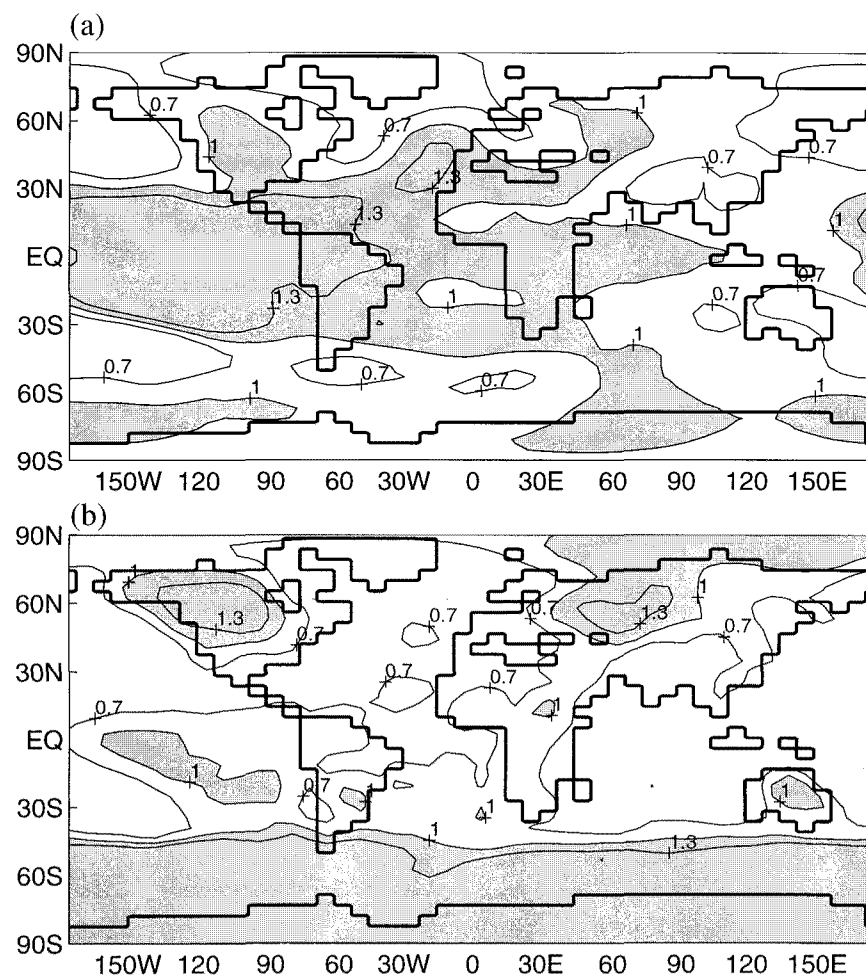


FIG. 5. The geographical distribution of the mass-weighted, vertically averaged regressions between local and global-mean temperature from the control unperturbed variability experiment for two cases. (a) Averaged over the mid- to upper troposphere (273–770 hPa). (b) Averaged over the lower troposphere (770–1013 hPa). Regions where the regressions exceed 1 are shaded.

of Fig. 4c also has a horizontal structure that is uniform with height. A warming at a given location is associated with a very similar warming aloft and therefore induces a large water vapor feedback. This is because global warming is the climate response to a steady, globally uniform forcing. Conversely, internally generated, global-mean temperature anomalies are a superposition of many modes of variability, whose individual impact is not geographically uniform, and that may not affect all parts of the troposphere equally. Thus the horizontal structure of an internally generated, global-mean anomaly does not persist as height increases and the water vapor feedback to such an anomaly is accordingly weaker.

## 6. Interaction between water vapor and other feedbacks

In section 5, we showed that water vapor feedback amplifies the model's global warming response to a

doubling of  $\text{CO}_2$  by a factor of 3.2. This is substantially greater than previous estimates of the impact of water vapor feedback. For example, Manabe and Wetherald (1967) showed that a radiative-convective model where relative humidity is fixed (analogous to our control model) was about twice as sensitive to an external forcing as a fixed absolute humidity model (analogous to our fixed  $\text{H}_2\text{O}$  model). Using nearly identical techniques, other modeling studies have arrived at similar results (see Ramanathan and Coakley 1978): water vapor feedback amplifies the climate response to an external forcing by approximately a factor of 2. Extrapolating from Raval and Ramanathan's (1989) observational estimate of the strength of water vapor feedback, Cess (1989) calculated that water vapor feedback would amplify  $\text{CO}_2$ -induced global warming by a factor of about 1.6. Although this calculation may not be perfectly accurate, since Raval and Ramanathan's estimate is based on the geographical variation of water vapor and surface temperature during only one month,



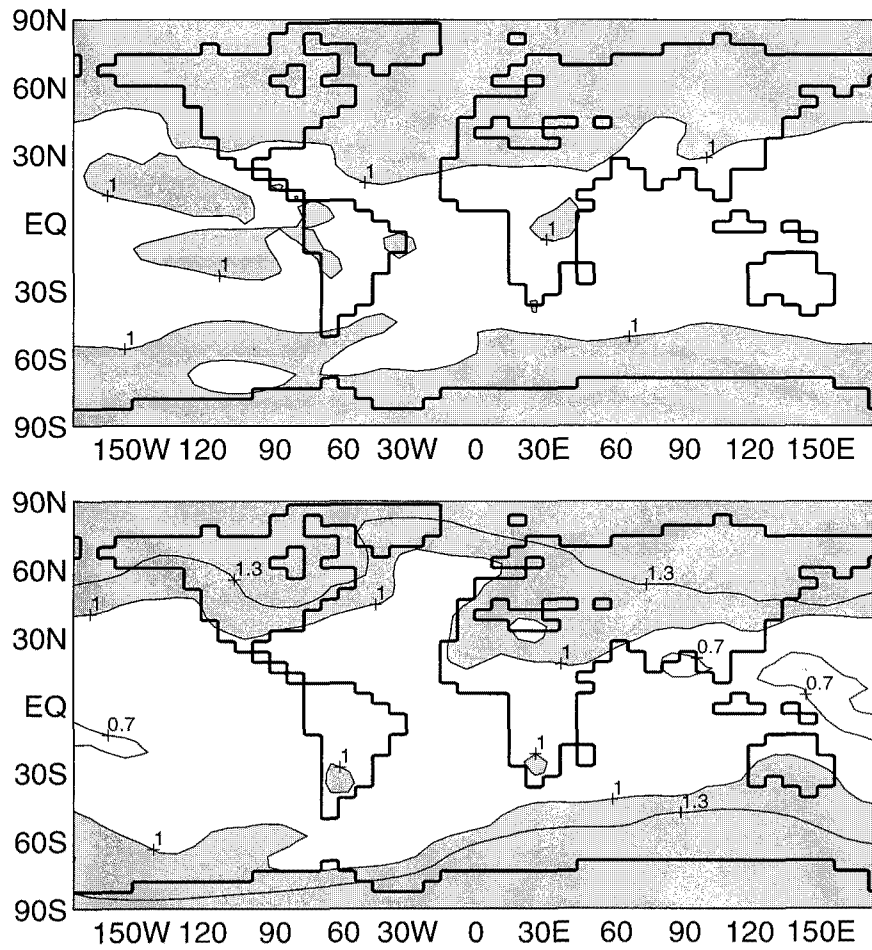


FIG. 6. The geographical distribution of the mass-weighted, vertically averaged ratio between local and global-mean warming due to  $\text{CO}_2$  doubling for two cases. (a) Averaged over the mid-to upper troposphere (273–770 hPa). (b) Averaged over the lower troposphere (770–1013 hPa). Regions where the ratio exceeds 1 are shaded.

it is nevertheless much lower than 3.2. In this section, we explain the discrepancy between our estimate of water vapor feedback's impact and those of previous studies.

The interaction between water vapor feedback and other feedback mechanisms is not taken into account in any of the above-mentioned studies. However, the model considered here does contain other feedback mechanisms, such as albedo and cloud feedback, that alter the impact of water vapor feedback. We may illustrate this point mathematically. Let  $T'_c$  be the equilibrium global warming response of the control model to a thermal forcing  $Q$ . Response  $T'_c$  can be related to  $Q$  through the sensitivity parameter of the control climate,  $\Lambda_c$ :

$$T'_c = \frac{Q}{\Lambda_c}. \quad (1)$$

An identical relationship exists among the equilibrium global warming response in the fixed  $\text{H}_2\text{O}$  model

( $T'_f$ ), the same thermal forcing  $Q$ , and the sensitivity parameter of the fixed  $\text{H}_2\text{O}$  climate,  $\Lambda_f$ :

$$T'_f = \frac{Q}{\Lambda_f}. \quad (2)$$

Thus the ratio of the warming in the two climates equals the inverse ratio of the sensitivities:

$$\frac{T'_c}{T'_f} = \frac{\Lambda_f}{\Lambda_c}. \quad (3)$$

We may rewrite Eq. (3) by expanding the sensitivity parameters in terms of contributions from various feedback mechanisms:

$$\frac{T'_c}{T'_f} = \frac{\Lambda_f}{\Lambda_c} = \frac{\lambda_o - \sum_f \lambda}{\lambda_o - \lambda_{w,hw} - \sum_c \lambda}. \quad (4)$$

Here  $\lambda_o$  represents the climate sensitivity parameter

that would result if no feedback mechanisms were in effect. This value is the change in outgoing longwave per degree centigrade that results from the temperature increase alone, as given by the Stefan–Boltzmann law. The mean climate for the two experiments prior to CO<sub>2</sub> doubling is nearly identical, so  $\lambda_o$  may be taken to be the same for both experiments. The variable  $\lambda_{w,lv}$ , which applies only to the control model, is the change to  $\lambda_o$  owing to the longwave effects of water vapor feedback. Here,  $\Sigma_c \lambda$  and  $\Sigma_f \lambda$  are the modifications to  $\lambda_o$  that arise from the other feedback mechanisms in the control and fixed H<sub>2</sub>O models, respectively. They each include contributions from albedo, cloud, and lapse rate feedbacks, which may not have the same strength in the two models.

We now divide both the numerator and the denominator of equation 4 by  $\lambda_o$ , which gives the contributions of feedback mechanisms to the two climate sensitivities in terms of nondimensional gain factors:

$$\frac{T'_c}{T'_f} = \frac{1 - \sum_f g}{1 - g_{w,lv} - \sum_c g}. \quad (5)$$

It is clear from Eq. (5) that impact of water vapor feedback, as measured by the ratio of the warmings, is affected not only by  $g_{w,lv}$ , the nondimensional longwave water vapor feedback parameter, but also by the contributions of other feedback mechanisms, as given by  $\Sigma_c g$  and  $\Sigma_f g$ . For this reason, it is desirable to understand how all feedback mechanisms contribute to the sensitivities of the control and fixed H<sub>2</sub>O climates. In so doing, we aim to explain why our estimate of water vapor feedback's impact is so much larger than previous estimates.

To carry out this quantitative evaluation of all feedback mechanisms, we calculated the radiative effects of the simulated changes in lapse rate, water vapor, cloudiness, and surface albedo upon CO<sub>2</sub> doubling using an off-line version of the model's radiative transfer subroutine. Starting with the temperature, water vapor, cloudiness, and surface albedo distributions averaged over years 401–500 of the unperturbed variability experiments, we calculated the global-mean net incoming solar and outgoing longwave radiation at the top of the atmosphere. Then, to focus on a particular feedback mechanism, we performed a second off-line calculation. For example, to assess the control model's albedo feedback, we imposed the mean surface albedo averaged over years 401–500 of the control global warming experiment and recalculated the net incoming global-mean solar radiation at the top of the atmosphere. We then divided the change in net incoming solar radiation resulting from the surface albedo decrease by the global-mean surface temperature change due to CO<sub>2</sub> doubling (3.38°C). This gave  $\lambda_a$ , the contribution of albedo feedback to the  $\Sigma_c \lambda$  terms shown in Eq. (4). Finally, we divided  $\lambda_a$  by  $\lambda_o$ , calculated based on the global-mean

TABLE 2. The gain factors for lapse rate, water vapor, cloud, and surface albedo feedbacks as calculated using the off-line radiation code.

|                       | Control | Fixed H <sub>2</sub> O |
|-----------------------|---------|------------------------|
| Lapse rate ( $g_l$ )  | 0.17    | 0.24                   |
| Water vapor ( $g_w$ ) | 0.39    | 0.07                   |
| Cloud ( $g_c$ )       | 0.14    | 0.10                   |
| Sfc. albedo ( $g_a$ ) | 0.12    | 0.11                   |
| Correction            | 0.01    | –0.00                  |

emission temperature of the model climate. This gave the gain factor  $g_a$  for albedo feedback. An analogous calculation was carried out for cloud and water vapor feedback. To quantify lapse rate feedback, the increase in global-mean outgoing longwave radiation at the top of the atmosphere due to the CO<sub>2</sub>-induced temperature change was divided by the temperature increase itself. This value was then subtracted from  $\lambda_o$ , the change in outgoing longwave radiation per degree Kelvin expected from the Stefan–Boltzmann law, thereby isolating the effects of CO<sub>2</sub>-induced changes in the vertical temperature structure. The entire procedure was repeated for the fixed H<sub>2</sub>O case for all feedbacks, except that the change in water vapor upon CO<sub>2</sub> doubling was not allowed to affect longwave radiation in the assessment of water vapor feedback.

The resulting values for the gain factors are shown in Table 2. The gain factors for lapse rate feedback are quite large in both models due to the large stratospheric cooling that occurs when CO<sub>2</sub> doubles. This reduces outgoing longwave radiation at the top of the atmosphere, thereby making lapse rate feedback positive. The gain factor is somewhat larger in the fixed H<sub>2</sub>O case because the stratospheric cooling is nearly identical in both models, so that the reduction in outgoing longwave radiation on a per degree centigrade basis is larger in the experiment with less warming. The fact that lapse rate feedback is positive and has a stronger effect in the model without water vapor feedback is a consequence of our choice to analyze the changes in radiative fluxes due to feedback mechanisms at the top of the atmosphere, rather than at the tropopause, as is often done. This unfortunately combines the effects of CO<sub>2</sub>-induced stratospheric cooling, which is not normally thought of as contributing to lapse rate feedback, and tropospheric lapse rate changes, which are. However, we were compelled to choose the top of the atmosphere as our reference level because of the difficulty of calculating radiative fluxes at the tropopause, which is often ill defined at high latitudes (Wetherald and Manabe 1988). The gain factor for water vapor feedback is slightly positive in the fixed H<sub>2</sub>O case because of the shortwave effect of water vapor feedback discussed in section 3. This effect also exists in the control case and is of similar magnitude (0.06). The remainder of the control gain factor is due to the longwave effects of water vapor. The gain factor for cloud feedback is positive in both

models. This is consistent with the results of Wetherald and Manabe (1988), who showed that the cloud feedback related to  $\text{CO}_2$  doubling in an atmosphere-mixed layer model whose atmospheric component is very similar to the present model is positive. In fact, the gain factor they calculate is very close to ours (0.11). Although the cloud feedback is slightly stronger in the control model, it is encouraging that the control and fixed  $\text{H}_2\text{O}$  gain factors agree as well as they do. This demonstrates that eliminating water vapor feedback has only a small effect on the magnitude of cloud feedback. The gain factors for albedo feedback are also very similar between the two models, although this is not surprising, since the models have approximately the same mean climate and therefore approximately the same mean sea ice and snow distributions.

In addition to the calculations discussed above, the temperature, water vapor, cloud, and surface albedo changes from the global warming experiments were imposed simultaneously and the global-mean, top-of-the-atmosphere solar and longwave radiative effects of these combined changes were computed using the off-line radiation code. These were then compared to the sum of the radiative effects of the temperature, water vapor, cloud, and surface albedo changes calculated separately. The difference between these two quantities, when divided by the global warming in the two experiments, provided corrections to  $\Lambda_c$  and  $\Lambda_f$  that arise from the radiative interaction of the feedback mechanisms. These corrections were in turn converted to gain factor corrections through division by  $\lambda_a$ . These values are listed in the last row of Table 2. The fact that these corrections are very small relative to the other gain factors is evidence that the feedback mechanisms can be measured separately through their effect on the atmosphere's radiative balance and then combined in a linear fashion without large error.

The radiative interaction of feedback mechanisms is small enough that their associated gain factors may be combined linearly to a fairly good approximation; however, the impacts of feedback mechanisms on the climate's temperature response to an external radiative forcing do not add up linearly, as predicted by Eq. (5). This point may be made more concrete by examining the ratio of the warmings predicted by the gain factors in Table 2. If the gain factors are inserted into Eq. (5), the ratio of the warmings is about 2.8, quite close to the actual ratio of 3.2. However, if the effects of cloud and albedo feedback, both of which are positive feedback mechanisms in this model, are removed from the calculation, the ratio falls to 1.6. Thus the presence of other positive feedback mechanisms enhances the impact of water vapor feedback on the warming. This is why our estimate of the effect of water vapor feedback on global warming is so much larger than previous estimates. This effect may also be seen by examining the geographical dependence of the  $\text{CO}_2$ -induced warming in the present models. Figure 7a shows the geographical

distribution of the ratio (control/fixed  $\text{H}_2\text{O}$ ) of the local surface warming that occurs by the final century of the global warming experiments. This plot represents the geographical dependence of water vapor feedback's impact on global warming. It is clear from the figure that water vapor feedback has its largest impact at high latitudes. In fact, the ratio of the warmings exceeds 4 over a significant portion of the globe poleward of  $50^\circ$ , especially in the Southern Hemisphere. This is precisely the part of the model world where snow and sea ice are present, especially in the winter. The reason why water vapor feedback has such a strong effect in these regions is because another important positive feedback mechanism, albedo feedback, is present here but not elsewhere.

Although it is not known whether the greenhouse-gas-induced change in cloudiness is a positive or negative feedback to surface temperature in the real climate, we have already noted that cloud feedback is positive in the context of the global warming simulated by both models. This result is consistent with the fact that the ratio of the warmings shown in Fig. 7a is somewhat larger than 2 even over most midlatitude and tropical locations, whereas the ratio predicted by the off-line version when both cloud and albedo feedback are absent was significantly less than 2 (1.6). Thus both cloud and albedo feedback enhance the impact of water vapor feedback in the global warming simulations. Our estimate of water vapor feedback's effect on global warming must therefore be viewed only in the context of the model's other feedback mechanisms. If the albedo or cloud feedbacks had been different in our model, the ratio of the warmings would also have been different.

Other feedback mechanisms affect the apparent impact of water vapor feedback in the unperturbed variability experiments as well. Our estimate of the strength of water vapor feedback in unperturbed variability, based on the control/fixed  $\text{H}_2\text{O}$  ratio of standard deviation of surface temperature, must therefore also be viewed in the context of the model's other feedback mechanisms. For example, the enhancement of water vapor feedback by albedo feedback may be seen by comparing the internally generated local variability of the two models. Figure 7b shows the geographical distribution of the ratio (control/fixed  $\text{H}_2\text{O}$ ) of the standard deviation of annual-mean surface temperature. Much of the high latitudes are covered by shaded regions, where the ratio exceeds 1.3. Water vapor feedback has a larger impact on the variability at these locations because albedo feedback comes into play. An analysis of the reason behind the large maximum in the ratio of the variability in the equatorial Pacific is beyond the scope of this paper. However, a model very similar to the control model is known to simulate a phenomenon resembling ENSO (see Knutson et al. 1997). Preliminary analysis, to be presented in a future paper, indicates that fixing water vapor in the radiative transfer subroutine suppresses significantly the model's ENSO-like phenome-

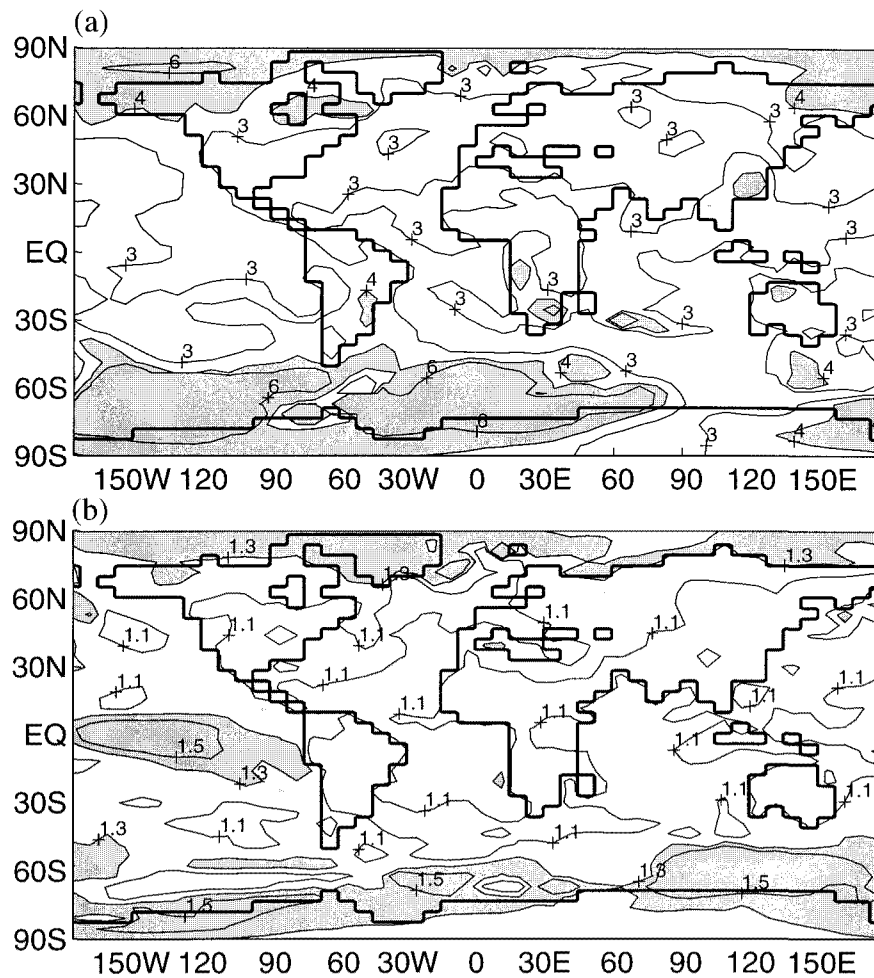


FIG. 7. (a) The geographical distribution of the ratio (control/fixed H<sub>2</sub>O) of the local surface warming that took place in the global warming experiments. The ratio was calculated in the following way. First, the average temperature over years 401–500 was calculated at each grid point for both the global warming and unperturbed variability experiments. Then the CO<sub>2</sub> induced warming was calculated at each grid point by taking the difference between these time-averaged values. This procedure was carried out for both control and fixed H<sub>2</sub>O cases and a ratio was taken at each grid point. Regions where the ratio exceeds 4 are shaded. In the fixed H<sub>2</sub>O global warming experiment, cooling actually occurred in a small region of the circumpolar ocean near 120°W. For the purposes of this contour plot, the ratio of the warming in this region was assumed to be greater than 6. (b) The geographical distribution of the ratio (control/fixed H<sub>2</sub>O) of the standard deviation of annual-mean surface temperature. Regions where the ratio exceeds 1.3 are shaded.

non. This drastically reduces surface temperature variability in this region.

In section 5, we compared the impact of water vapor feedback on internally generated anomalies and global warming by comparing the ratio of standard deviation of surface temperature to the ratio of global warming. However, the results of this section make it clear that both of these ratios are affected by other feedback mechanisms. Moreover, the magnitude and sign of the other feedbacks may not be the same in the unperturbed variability and global warming contexts. Thus the ratio of the warmings could be larger than the ratio of the standard deviations because the net strength of the other feedbacks is more positive in the global warming con-

text. Although this is unlikely to account for the large difference in the ratios, it is nevertheless desirable to verify that the difference in the strength of water vapor feedback is mainly responsible for the disparity in the ratios, and that our explanation for the larger impact of water vapor feedback on greenhouse-gas-induced climate change presented in section 5 is therefore robust. A detailed analysis of all feedback mechanisms in the unperturbed variability experiments is a complicated issue that is beyond the scope of this paper. However, it is simple to estimate the radiative strength of water vapor feedback in unperturbed variability using the off-line version of the radiative transfer code. Such a calculation facilitates a quantitative comparison of the ra-

diative impact of water vapor feedback in natural variability and global warming contexts isolated from the effects of the other feedbacks. To perform this task, we first regressed annual-mean water vapor time series of the control unperturbed variability experiment at every grid point and vertical level with annual-mean, global-mean surface temperature. These regressions provide a measure of the changes in water vapor that occur throughout the model atmosphere for a global-mean surface temperature anomaly of  $1^{\circ}\text{C}$ . These water vapor anomalies were then imposed on the off-line radiative transfer code and the resulting global-mean decrease in outgoing longwave radiation was calculated. This decrease, when divided by  $\lambda_o$ , gives the gain factor associated with water vapor feedback in natural variability. Using this method, we calculated a gain factor of 0.18 for the longwave effects of water vapor feedback. The global warming counterpart to this gain factor has a value of 0.33 (gain factor listed in Table 2 for water vapor minus the gain factor associated with the short-wave effects of water vapor). This calculation confirms that water vapor feedback is nearly twice as effective in the global warming context, whatever the magnitude and sign of the other feedbacks may be.

## 7. Conclusions

### a. Summary

Here we summarize the picture of water vapor feedback that emerges from our experiments. In section 4, we showed that the control model has more internally generated surface temperature variability on all spatial scales and timescales than its fixed  $\text{H}_2\text{O}$  counterpart. Thus water vapor feedback is positive in the context of the model's unperturbed variability. However, the control/fixed  $\text{H}_2\text{O}$  ratio of standard deviation of surface temperature increases as spatial scales increase. This implies that water vapor feedback is more effective the larger the spatial scale. The degree to which a surface temperature anomaly of a given spatial scale penetrates the troposphere is a critical factor in explaining the spatial-scale dependence of its associated water vapor feedback: global-mean anomalies penetrate more deeply into the troposphere than local ones. Since relative humidity does not change very much as surface temperature fluctuates, this implies a stronger relationship between tropospheric absolute humidity and surface temperature on large scales than small. Water vapor feedback may also become less important at smaller scales because much of the damping of surface–troposphere anomalies is accomplished by horizontal advection of sensible and latent heat, rather than radiative processes, diluting the effects of water vapor feedback.

In section 5, we confirmed that the model's water vapor feedback is also positive in the context of global warming. The equilibrium global warming at the surface due to a doubling of  $\text{CO}_2$  in the control experiment was

$3.38^{\circ}\text{C}$ , while for the fixed  $\text{H}_2\text{O}$  case the warming was only  $1.05^{\circ}\text{C}$ . Thus the suppression of internally generated variability by removing a positive feedback also has the effect of reducing the climate sensitivity to an increase in greenhouse gases. However, we also noted that the ratio of equilibrium global warming (control/fixed  $\text{H}_2\text{O}$ ) is significantly larger than the ratio of standard deviation of surface temperature in the unperturbed variability experiments at the global spatial scale. Thus the model's water vapor feedback is more effective in global warming than unperturbed variability. Like the explanation for the dependence of water vapor feedback on spatial scale, this difference is rooted in the discrepancy between the tropospheric distribution of the warming in the global warming experiment and the characteristic tropospheric structure of temperature anomalies in the unperturbed variability experiment. In the global warming case, the temperature increase extends throughout the troposphere, whereas in the unperturbed variability case, a typical surface temperature anomaly tends to decrease in amplitude with height. At the same time, simulated surface temperature changes tend to induce very little change in tropospheric relative humidity in both unperturbed variability and global warming cases. For global warming and internally generated temperature anomalies of identical magnitude, there is therefore a smaller change in atmospheric humidity, and hence absorptivity, associated with the internally generated anomaly.

In this section, we also shed light on the reason why internally generated, global-mean temperature anomalies do not penetrate as effectively into the troposphere as the warming induced by a doubling of  $\text{CO}_2$ . We showed that when  $\text{CO}_2$  increases, the lower-tropospheric warming at a given location is associated with a very similar warming aloft. Thus the global-mean warming is uniform throughout the troposphere as well. Conversely, the regions contributing most to internally generated, global-mean variability in the lower troposphere do not correspond to the regions that contribute most to internally generated, global-mean variability in the mid- to upper troposphere. Temperature fluctuations in the regions that dominate the mid- and upper-tropospheric global-mean variability are most likely only weakly related to temperature fluctuations in the distant regions that dominate the global-mean variability in the lower troposphere. The regression between global-mean tropospheric temperature and surface temperature therefore decreases with height. This points to a difference—of fundamental importance for water vapor feedback—between internally generated, global-mean temperature variability and the global-scale temperature anomaly that results from an increase in  $\text{CO}_2$ ; internally generated, global-mean temperature anomalies at any level of the troposphere are a superposition of many modes of variability, whose individual impact is not geographically uniform, and that may not affect all parts of the

troposphere equally. Global warming, on the other hand, is the response to a steady, globally uniform forcing.

Since water vapor feedback has a different impact on internally generated and greenhouse-gas-forced temperature anomalies, it is not straightforward to estimate the climate sensitivity to a doubling of  $\text{CO}_2$  based on an analysis of internally generated variability alone. This fact has implications for previous studies. For example, Wigley and Raper (1990) examined low-frequency variability in stochastically forced energy balance models of various sensitivities to assess the probability that the warming trend in global-mean temperature observed over the past 100 yr is internally generated. However, their energy-balance model has the same sensitivity to an increase in greenhouse gases as it does to the low-frequency stochastic forcings they imposed to mimic internally generated, global-mean temperature fluctuations. Our study indicates that this assumption does not apply to the real climate.

The results of sections 4 and 5 are consistent with the original hypothesis that, for the purposes of quantifying the effects of water vapor feedback on surface temperature, water vapor in the model atmosphere is essentially controlled by the Clausius–Clapeyron equation. Whether the context is unperturbed variability or global warming, a surface temperature change is associated with very little change in relative humidity aloft and the atmospheric water vapor content tends to remain proportional to the water vapor storage capacity of the atmosphere. Given this observation, what controls the strength of water vapor feedback is the degree to which a surface temperature anomaly penetrates the troposphere. The more it penetrates, the stronger the water vapor feedback. In the real climate, relative humidity may deviate from constant values to a greater degree than in the model as surface temperature fluctuates (Sun and Held 1996). The vertical structure of a surface–troposphere temperature anomaly is nevertheless a useful starting point from which to gauge the expected strength of its associated water vapor feedback, whether the context is a numerical model or the real climate. This conclusion is consistent with the work of Bony et al. (1995), who analyzed the relationships between tropospheric water vapor, outgoing longwave radiation, and surface temperature in satellite data and output from model experiments in which  $\text{CO}_2$  was doubled and the solar constant was increased by 2%. They found that the relationships among these three variables were different depending on whether the type of climate variation under consideration was seasonal and interannual variability, or climate change due to some external forcing. They attributed these differences to the fact that the tropospheric lapse rate behaves differently in the various cases.

In section 6, we examined the interaction between water vapor feedback and other feedback mechanisms. We showed that other feedbacks alter the impact of water vapor feedback. To quantify this effect, we calculated

the radiative impacts of all feedbacks in the  $\text{CO}_2$ -induced warming of both models using an off-line version of the model's radiative transfer code. We showed that the surface albedo and cloud feedbacks are positive in both the control and fixed  $\text{H}_2\text{O}$  cases. They therefore act to enhance the apparent impact of water vapor feedback. This interaction among feedback mechanisms explains why our rather large estimate of water vapor feedback's impact on global warming is not in contradiction to previous estimates, which are based on the assumption that water vapor feedback is the only feedback operating and are therefore smaller. Our estimates of the impact of water vapor feedback on unperturbed temperature variability are also affected by the other feedbacks. We therefore verified that it is the difference in water vapor feedback, rather than the other feedbacks, that is the main reason why the control/fixed  $\text{H}_2\text{O}$  ratio of the warming is so much larger than the control/fixed  $\text{H}_2\text{O}$  ratio of unperturbed variability. Using the off-line radiation code, we demonstrated that the changes in water vapor associated with a global mean surface temperature anomaly reduce the radiative damping of surface temperature about half as much as the increase in water vapor associated with a  $\text{CO}_2$ -induced global warming anomaly of the same magnitude. This was additional confirmation that water vapor feedback is much stronger in the global warming context. Since the other feedbacks affect the apparent impact of water vapor feedback and may not be perfectly simulated by this model, our estimates of the effect of water vapor feedback should not be taken too literally. Our main conclusions regarding the spatial-scale dependence of water vapor feedback and its differing impact on unperturbed variability and global warming are meant to be robust in a qualitative sense.

#### *b. Discussion: Comparison of observed and modeled variability*

In this final section, we place the model's water vapor feedback in the context of the real climate. We assess the realism of the model's water vapor feedback by comparing the surface air temperature variability in the simulations with and without water vapor feedback to the observed surface temperature record. This comparison will allow us to address the following question: Is the model's water vapor feedback necessary to simulate the observed levels of variability?

Figure 8 shows the geographical distribution of standard deviation of annual-mean surface air temperature ( $^{\circ}\text{C}$ ) for three cases: the control unperturbed variability experiment, the observed, and the fixed  $\text{H}_2\text{O}$  unperturbed variability experiment. Although the calculations shown in this figure are based on surface air temperature, rather than surface temperature itself, as elsewhere in this study, the two variables are very tightly linked everywhere on the globe on timescales longer than a few years. For example, analyzing a very similar model,

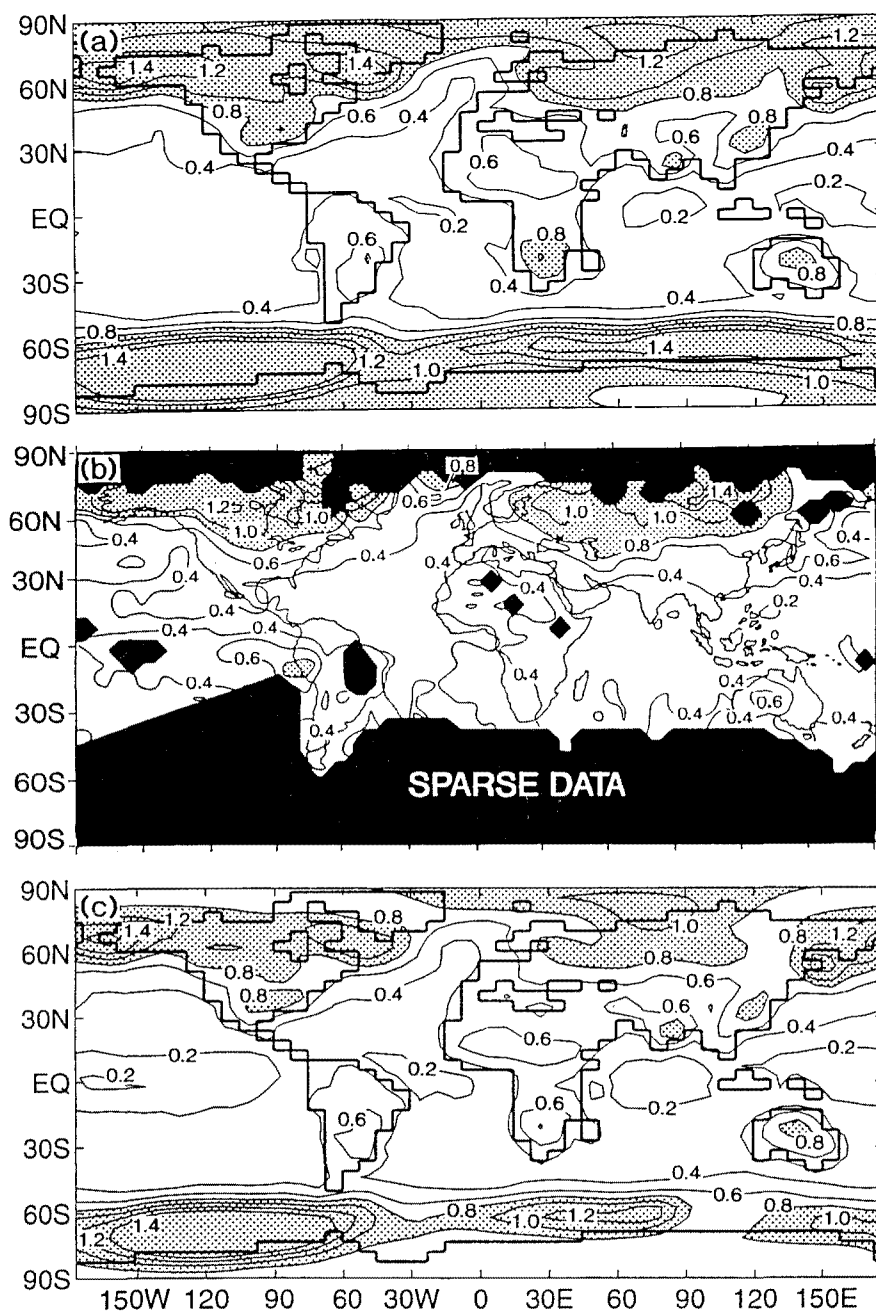


FIG. 8. The geographical distribution of standard deviation of annual-mean surface air temperature (°C) for three cases. (a) The control unperturbed variability experiment. (b) The observed standard deviation, as calculated from a 110-yr time series compiled by Jones and Wigley (1991). The standard deviations were calculated by Stouffer et al. (1994), who used the following method. They obtained annual-mean temperature values at those grid points, spaced 5° apart, where at least 10 monthly mean values are available. Standard deviations were then calculated at those grid points where at least 33 annual-mean values are available. (c) The fixed H<sub>2</sub>O unperturbed variability experiment.

Manabe and Stouffer (1996) showed that the average spectrum of local sea surface temperature is nearly identical to the average spectrum of local surface air temperature at timescales longer than about two years. The

same would be true at land points at even shorter time-scales since the model's land surface has no heat capacity. Thus for the purposes of measuring the low-frequency variability at or near the surface, the two

variables may be used as surrogates for one another. The use of surface air temperature here was dictated by the lack of availability of surface temperature data, particularly over land, where surface air temperature is more commonly measured.

In the mid- to high latitudes of the Northern Hemisphere, both the fixed  $H_2O$  and control integrations do a reasonable job of simulating the observed variability. For example, in Fig. 8, the  $0.8^\circ\text{C}$  contours of the fixed  $H_2O$  and control cases over the North American and Eurasian continents agree equally well with the observed, although they differ somewhat from one another. At the same time, the  $0.4^\circ\text{C}$  contours in the North Atlantic agree very well among all three cases. The control experiment shows much more variability in the high latitudes of the Southern Hemisphere than its fixed  $H_2O$  counterpart; unfortunately, the observed data necessary to identify the more realistic simulation do not exist in this region. In the Tropics, the standard deviations over land from both experiments agree reasonably well with the corresponding observed standard deviations, so that both models do a respectable job of simulating the observed variability in these regions. In the equatorial Pacific, the standard deviation of surface air temperature in both model configurations is noticeably less than the observed. This is because the model's ENSO-like phenomenon is weaker than observed (Knutson and Manabe 1997). However, this disagreement with observations is much more apparent in the fixed  $H_2O$  case, which actually shows a minimum in standard deviation in this region. In addition, the standard deviation in the fixed  $H_2O$  case is less than  $0.2^\circ\text{C}$  in more areas than either the observed or the control case in the other tropical zones, although the difference is not large.

With the exception of the equatorial Pacific and to a lesser extent the other tropical ocean regions, it cannot be claimed that the control experiment is more realistic than the fixed  $H_2O$ ; water vapor feedback simply does not have enough impact on local temperature variability to identify one of the two experiments as the more realistic simulation. This leaves open the question of whether water vapor feedback is necessary to reproduce observed levels of variability. However, the picture should be different if global-mean temperature variability is considered. In section 4, we established that water vapor feedback is more effective on larger spatial scales than small. Therefore, an examination of global- rather than local-scale anomalies ought to result in a larger difference between the two unperturbed variability experiments, which will hopefully establish one of the models as the more realistic one. In Fig. 9, we plot the time series of global-mean, annual-mean surface air temperature for four cases. Figure 9a shows the observed time series over the past 110 yr. This time series may be regarded as the observed unperturbed variability, assuming that the warming trend it contains is an internally generated fluctuation of the climate system. Figure 9b shows the same time series with the warming

trend removed. This time series may be regarded as the observed unperturbed variability, assuming that the warming trend of the top panel is entirely due to external forcing. Figures 9c and 9d show the last 400 yr of the control and fixed  $H_2O$  time series.

The standard deviations for each time series are shown in their respective panels. With a standard deviation of  $0.211^\circ\text{C}$ , the undetrended observed time series exhibits by far the most variability. The large standard deviation is almost entirely due to the warming trend. The detrended observed time series has less variability, with a standard deviation of  $0.128^\circ\text{C}$ . The control time series has approximately the same standard deviation as the detrended observed time series ( $0.127^\circ\text{C}$ ), while the fixed  $H_2O$  time series has the least variability of all, with a standard deviation of  $0.083^\circ\text{C}$ . The relative magnitude of the standard deviations of the two time series from the unperturbed variability experiments is consistent with the results presented in section 4: The presence of water vapor feedback enhances significantly global-scale surface air temperature variability.

We begin the discussion of these results by assuming that the observed warming trend is an internally generated fluctuation and that the topmost panel therefore represents unperturbed variability of surface temperature. Given this assumption, it is clear from both visual inspection of the fixed  $H_2O$  and undetrended observed time series and a comparison of their standard deviations that the model without water vapor feedback does not have enough internally generated variability to reproduce the sort of temperature fluctuation seen in the observed undetrended time series. At the same time, the standard deviation of the fixed  $H_2O$  time series is also substantially less than that of observed time series with the warming trend removed. Even after minimizing the standard deviation of the observed time series by making the opposite assumption that the warming trend is externally forced, the fixed  $H_2O$  model still fails to reproduce the observed unperturbed variability. Therefore, no matter whether we assume the observed trend is internally generated or externally forced, we are unable to simulate the observed global-mean variability without water vapor feedback.

We may make a similar comparison between the observed variability and the control time series. Assuming, again, that the observed warming trend of Fig. 9a is an internally generated fluctuation, the control run also fails to reproduce the observed variability. Not only is the standard deviation of the observed, undetrended time series nearly 70% greater than that of the control case, but nowhere in the control time series is there such a large and sustained trend as is seen in Fig. 9a. This result is consistent with the work of Stouffer et al. (1994), who assessed the probability that a very similar model could reproduce the observed century-scale warming trend without any external forcing. They found that for intervals longer than about 60 yr, no trends as large as the observed trend ( $0.5^\circ\text{C century}^{-1}$ ) can be found in a 1000-yr time series of surface air temperature.



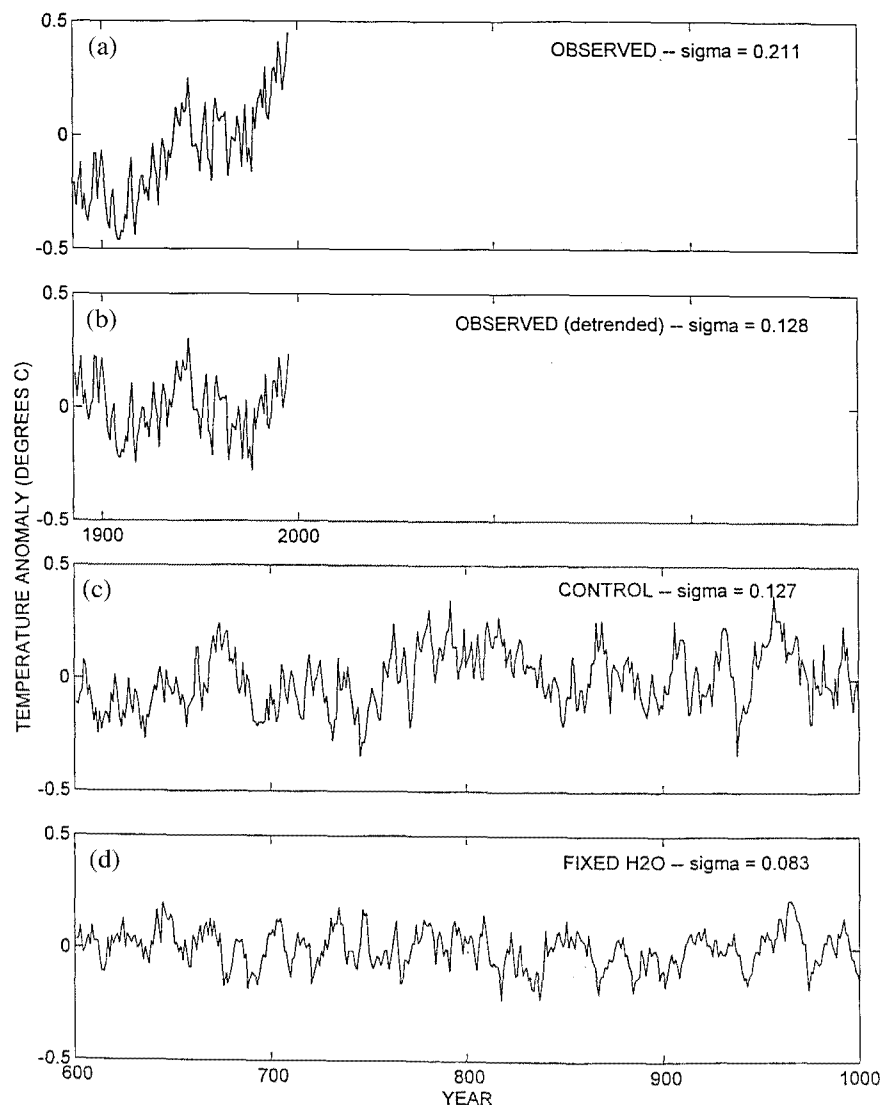


FIG. 9. The time series of global-mean, annual-mean, surface air temperature for four cases. (a) The observed time series over the past 110 yr. (b) The same time series as in (a) with the warming trend removed. The trend was assumed to be linear. (c), (d) The last 400 yr of the control and fixed  $H_2O$  time series. The standard deviations for each time series are shown in their respective panels.

Therefore, even with water vapor feedback included, the model still cannot reproduce a fluctuation of the type shown in the topmost panel. The other alternative is to assume the warming is externally forced. In this case, the standard deviations of the control and observed detrended time series agree quite well (although their near-perfect agreement is certainly fortuitous). While a comparison with the observed record reveals definitively that we are unable to simulate the observed levels of variability without water vapor feedback, the model with water vapor feedback has about the right amount of global-scale variability if the observed warming trend is assumed to arise from external forcing.

*Acknowledgments.* The authors wish to thank Isaac Held, Jerry Mahlman, Brian Soden, and Ron Stouffer for many helpful discussions as well as constructive criticism of the manuscript before it was released for publication. In addition, the article was greatly improved as a result of the comments of two reviewers, Graeme Stephens and Simon Tett. Alex Hall was supported by a NASA Earth System Science Fellowship while this research was being carried out. Observed global-mean surface temperature data were compiled by the Climate Research Unit of the University of East Anglia (United Kingdom) and obtained from their Web site: <http://www.cru.uea.ac.uk:80/cru/data/temperature.htm>.

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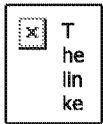
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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/21/2025 2:03:50 PM  
**To:** Judith Curry [curry.judith@gmail.com]  
**CC:** Steve Koonin [steven.koonin@gmail.com]; John Christy [climatemanager60@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: ch 4 revisions

What is the citation indicated as a superscript 33?

On Wed, May 21, 2025 at 9:31 AM Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:  
attached, added text in red

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Judith Curry, President  
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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Wednesday, May 21, 2025 9:31 AM  
**To:** Steve Koonin; Ross McKittrick; John Christy; Roy Spencer; Travis Fisher  
**Subject:** ch 4 revisions  
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## 4 Climate Sensitivity to CO<sub>2</sub> Forcing

### Chapter Summary

*There is growing recognition that climate models are not fit for the purpose of determining the Equilibrium Climate Sensitivity (ECS) of the climate to increasing CO<sub>2</sub>. The IPCC has turned to data-driven approaches using historical data and paleoclimate reconstructions, but their reliability is diminished by data inadequacies.*

*Data-driven ECS estimates tend to be lower than climate model-generated values. The IPCC AR6 upper bound for the likely range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by paleoclimatic data. The IPCC AR6 lower bound for the likely range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound is more weakly justified. Evidence since the AR6 finds the lower bound of the likely range to be around 1.8°C.*

### 4.1 Introduction

The climate's response to increasing concentrations of CO<sub>2</sub> is central to the scientific debate on anthropogenic climate change, and so also to the public debate on "climate action." The simplest measure of that response is the rise in the global average surface temperature, quantified by the Equilibrium Climate Sensitivity (ECS). ECS is defined as the amount of warming expected in response to a doubling of CO<sub>2</sub> from its pre-industrial concentration of 280 ppm, after all climate components have had time to adjust. Some components, like temperatures in the lower atmosphere (troposphere), adjust rapidly, while others such as the deep ocean and cryosphere might take as long as centuries. A related measure, the Transient Climate Response (TCR), better describes the shorter time scales; it is defined as the amount of warming when the CO<sub>2</sub> concentration is doubled by rising one percent annually for 70 years.

The 1979 Charney Report for the US National Academy of Sciences (Charney *et al.* 1979) proposed that the most likely ECS was  $3.0 \pm 1.5^\circ\text{C}$ . The IPCC repeatedly reaffirmed that range with only minor variations until its most recent AR6. AR5 termed 1.5 -- 4.5°C as the *likely* range (66 percent probability) and stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C.

The uncertainty in ECS has remained stubbornly wide, despite many individual studies that claimed to narrow it. Most recently, AR6 narrowed the *likely* range to 2.5–4.0°C and deemed the *very likely* range to be 2.0 - 5.0°C. This narrowing on the low end is disputed, as will be discussed below.

Uncertainties in ECS are highly consequential for policy making. As will be discussed in Chapter 11, economic models use ECS values to project the costs of CO<sub>2</sub> emissions. The traditional value (3.0 °C) has typically yielded modest global social costs of CO<sub>2</sub> emissions, sufficient to justify some policy actions, but mostly deferred to later in this century. If ECS is very high (above 4.5°C) immediate aggressive emission controls become more imperative, whereas no CO<sub>2</sub> emission controls are economically justifiable for ECS below 2.0°C (Dayaratna et al. 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

Climate scientists use multiple lines of evidence to determine the Equilibrium Climate Sensitivity:

- Climate model simulations
- Historical observations

- Paleoclimatic observations
- Process understanding of feedbacks

By itself, the equilibrium warming effect of a doubling of atmospheric CO<sub>2</sub> is slightly more than 1°C.<sup>33</sup> The large values of ECS arise from positive feedbacks that amplify the warming effect of CO<sub>2</sub>. Water vapor feedback is positive: a warmer atmosphere may have more water vapor, which itself is a powerful greenhouse gas. Water vapor feedback is partially canceled by the fact that atmospheric temperature decreases more slowly with height above the Earth's surface when atmospheric water vapor increases. Warmer temperatures also result in less snow and sea ice cover, allowing the Earth to absorb more of the sun's radiation. Some simple estimates of these three feedbacks increase the ECS to around 2°C (Sherwood et al., 2020).

Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

#### 4.2 Model-based estimates of climate sensitivity

The ECS ranges given in IPCC AR4 and AR5 were obtained primarily by examining the behaviour of large-scale climate models, also called General Circulation Models (GCMs). However, the IPCC changed course in its AR6 when it turned to a more direct data-driven methodology. Here we discuss some of the pitfalls of using GCMs to try to determine the Earth's climate sensitivity.

ECS is an emergent property of climate models—that is, it is not directly parameterized or tuned. Historically, collections of parameterizations have been chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes, particularly in AR4 and to a lesser extent in AR5. Otherwise plausible GCMs and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, even in a CMIP6 model, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model (emphasis added):

“We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, as opposed to tuning the aerosol forcing.”

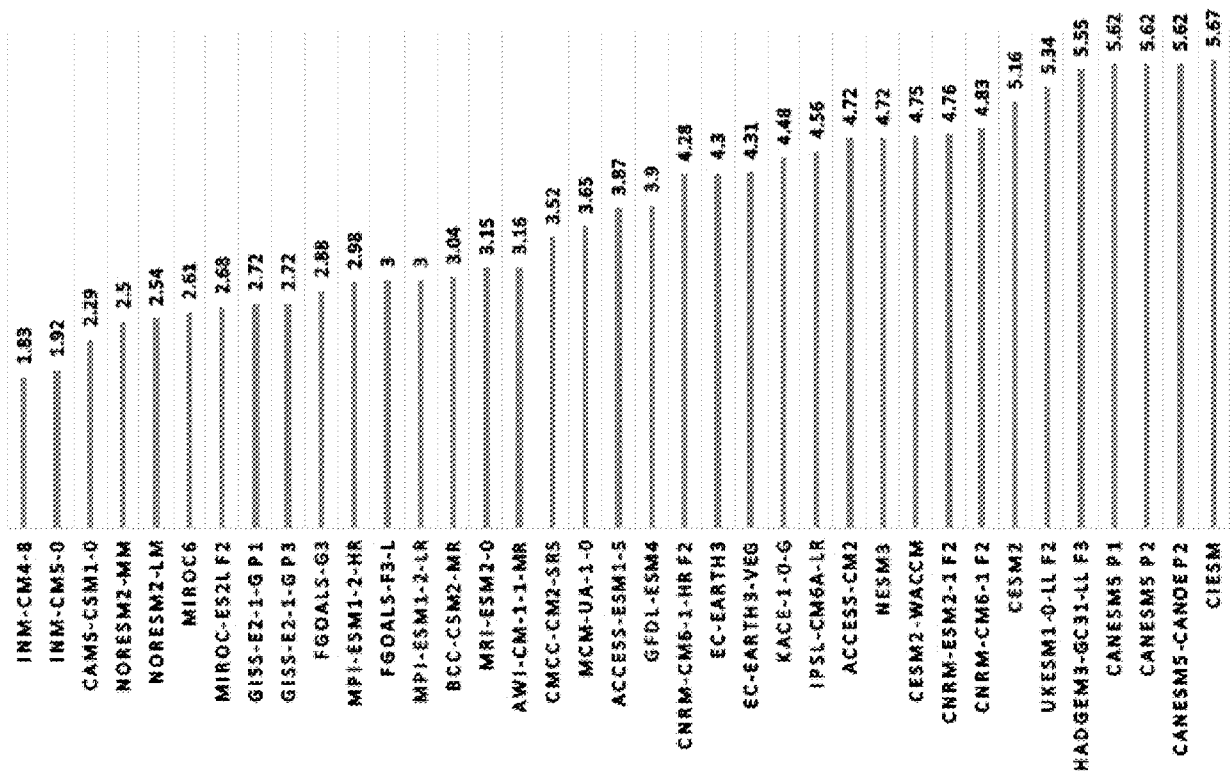
In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

Direct warming from CO<sub>2</sub> doubling is only about 1°C (Hall and Manabe 1997); further warming arises from climate feedbacks that are not explicitly resolved by the GCM but rely on parameterizations of physical processes. Higher values of ECS arise primarily from assumed positive cloud feedbacks,

whereas the magnitude and even the sign of the feedbacks are very uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for GCMs to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub> and allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, “effective climate sensitivity” is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>.

The spread of ECS values from the CMIP5 ensemble of climate models used in the AR5 was 2.0–4.7°C; that range increased for the CMIP6 models used in the AR6 to between 1.8 and 5.7°C (Chen et al, 2021, Scaffeta 2021, see Figure 5.1). Far from settling the model-based sensitivity of climate system uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka et al, 2020)



**Figure 4.1** Equilibrium Climate Sensitivities in °C of 37 climate models from the CMIP6 ensemble. Identifiers for the various models appear along the horizontal axis. From (Scafetta, 2021) <https://www.mdpi.com/2225-1154/9/11/161>

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on other methods, chiefly a recent empirical estimate.

#### 4.3 Data-driven estimates of climate sensitivity

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past (Otto et al., 2013). Using this information, a simple empirical model called an Energy Balance Model can be employed. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20<sup>th</sup> century warming can be shown to be consistent either with low ECS and low aerosol cooling, or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time, the IPCC's estimate of the cooling effect of aerosols has declined (Lewis 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates based on historical data appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For the AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical and paleoclimate proxies with the process-based approach and yielded a best estimate of 3.1°C, with a *likely* range of 2.6–3.9°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).



An argument emphasized in AR6 is that data-driven ECS estimates might understate the future warming response to GHGs because of a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to strongly influence the overall efficiency with which the Earth radiates heat to space, but some regions remove heat more efficiently than others. If the west-to-east temperature gradient in the tropical Pacific is weakened in a warming climate, warming would concentrate where heat is less efficiently removed, raising ECS.

Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value. However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be *lower* than current estimates.

## 5.5 Transient Climate Response

The Transient Climate Response (TCR) provides a more useful observational constraint on climate sensitivity. TCR is the amount of warming that results when CO<sub>2</sub> is increased at an annual rate of 1 percent over a period of 70 years (i.e., doubled gradually). Relative to the ECS, observationally determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. In contrast to ECS, the upper bound of TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) are 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

As will be discussed in Chapter 6, a real-world ECS smaller than the model average is supported by studies that show climate models on average overestimate the observed surface and troposphere warming over the past 50 years. Lower sensitivities also align with evidence from consistent fingerprinting (Section 8), where model responses need to be downscaled to align with observed trends.

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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/18/2025 4:06:56 PM  
**To:** Judith Curry [curry.judith@cfanclimate.com]  
**CC:** Roy Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; John Christy [climateman60@gmail.com]; Steve Koonin [steven.koonin@gmail.com]  
**Subject:** Re: Authors' preface?

We have a Foreword already that explains a bit about how the project began and states that we wrote without editorial oversight. In general I would say that with the Preface or Foreword, less is more. We especially need to avoid anything that strikes a defensive tone or makes it sound like we're looking for establishment approval. While we might be in for a pleasant surprise in that regard, we shouldn't be under any illusions.

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Below are some fragments of points I would want to include if we did have such a section. No doubt you all can come up with others.

Thoughts? If we decide to do this, I'd volunteer to draft some readable text.

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Good policy needs good science

Energy transition is motivated in large part by an alleged scientific consensus that Climate is already broken due to an increase in extreme weather and that a climate catastrophe is likely, or at least possible, if GHGs are allowed to continue

We are five scientists with some 200 years of research experience and XX published peer reviewed papers among us, the great majority of it focused on weather and climate issues.

We are intimately familiar with the concepts, the data, the literature, and climate science community. On that basis, we can say climate isn't broken and catastrophe is highly unlikely.

Further, that's largely consistent with the UN and USG assessment reports (although not with the reports' summaries for policymakers). That readers might find such statements surprising is a testament to how poorly and incorrect are media and political statements about climate and emissions.

For those reasons, we undertook the task. Paid particular attention for display primary data or simulation results over long periods of time in graphical form. That's important to separate out the long-term natural fluctuations of the climate and extreme weather events from any effects due to growing human influences on the climate. Also emphasized graphical displays rarely seen in popular documents.

While we've high confidence in the correctness of what we've written, we expect, and in fact welcome, thoughtful criticism of this draft. A public, adult conversation by scientists about climate science is long overdue. That process will enhance the quality of the final report.

Our thanks to Travis and ?? for help in the production ...

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Saturday, May 17, 2025 2:10 PM  
**To:** 'Judith Curry'; 'John Christy'; 'Roy W. Spencer'; 'Ross McKittrick'  
**Cc:** 'Travis Fisher'  
**Subject:** Authors' preface?

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SEK

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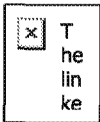
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**Sent:** Wednesday, May 21, 2025 6:21 AM  
**To:** 'Travis Fisher'; 'Ross McKittrick'  
**Cc:** 'Judith Curry'; 'Roy Spencer'; 'John Christy'  
**Subject:** RE: Title  
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your privacy,  
Outlook Office  
prevented  
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download of this  
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Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

---

**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 20, 2025 8:52 PM  
**To:** Ross McKittrick  
**Subject:** Re: Title

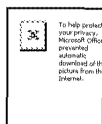
I'm fine with it

On Tue, May 20, 2025 at 3:32 PM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
I have the following as a placeholder in the template document

- An Assessment of the Risks Posed by Carbon Dioxide Emissions on the United States of America

Travis suggested this might be improved upon. Any suggestions?

--



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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Tuesday, May 20, 2025 7:09 PM  
**To:** Steven Koonin; 'Ross McKitrick'; 'Judith Curry'; 'John Christy'; 'Travis Fisher'  
**Subject:** RE: Title

Cool with me.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Date:** 5/20/25 6:08 PM (GMT-06:00)  
**To:** 'Roy Spencer' <roywspencer@hotmail.com>, 'Ross McKitrick' <ross.mckitrick@gmail.com>, 'Judith Curry' <curry.judith@gmail.com>, 'John Christy' <climateman60@gmail.com>, 'Travis Fisher' <travis.scott.fisher@gmail.com>  
**Subject:** RE: Title

“Carbon Dioxide” rather than “Greenhouse Gas” ? , since we’ve concentrated on the former

SEK

---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Tuesday, May 20, 2025 6:53 PM  
**To:** Ross McKitrick <ross.mckitrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@gmail.com>  
**Subject:** RE: Title

Updated Scientific Assessment of the Risks to Human Health and Welfare from U. S. Greenhouse Gas Emissions

Sent from my Verizon, Samsung Galaxy smartphone

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**From:** Ross McKitrick <ross.mckitrick@gmail.com>  
**Date:** 5/20/25 5:33 PM (GMT-06:00)

To: Judith Curry <curry.judith@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>, Steven Koonin <steven.koonin@gmail.com>  
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**Subject:** Title

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Thursday, May 15, 2025 4:11 PM  
**To:** John Christy  
**Subject:** Re: NE Precipitation -update

OK. While you're at it please have a look at the lat/lon for the Maine stations. You were concerned they weren't placed on the map correctly.

On Thu, May 15, 2025 at 4:06 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:  
Ross

I'm working on adding stations to the Northeast set because I'm a little concerned that 21 stations might not give the most robust result. Whatever I have by tomorrow (Friday) afternoon is what I will send and then you can rerun the numbers for that part of the analysis. I have 23 stations at this point, but want a few more. This is more time consuming than I had thought because so many stations which have fairly long records are not keyed-in in the earliest years.

John C.

---

**From:** John Christy <climateman60@gmail.com>  
**Sent:** Thursday, May 15, 2025 4:07 PM  
**To:** Ross McKittrick  
**Subject:** NE Precipitation -update

Ross

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John C.

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Thursday, May 15, 2025 6:55 PM  
**To:** Steven Koonin  
**Cc:** Travis Fisher; Roy W. Spencer; John Christy; Judith Curry  
**Subject:** Re: Ch 2

Steve you should write a Figure caption for the chapter explaining that.

On Thu, May 15, 2025 at 6:33 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

On Figure 2.2:

I constructed that figure from Figure 3 on pg 192 of this paper: <https://ajsonline.org/article/61570-geocarb-iii-a-revised-model-of-atmospheric-co-2-over-phanerozoic-time>

As you can see from the penultimate paragraph on pg 191 of that paper, “a rough value of 300 ppm” is used to represent the present. So “today” would plot as 1.3 on the graph. In fact, here is the caption from the figure as it appears in “Unsettled”

**Figure 3.3 Atmospheric concentration of carbon dioxide**

**beginning at 550 million years ago.** Values determined from the isotopic ratio in carbonate sediments and fossilized soils are relative to the average over the past few million years; today’s concentration would be about 1.3 on this scale, down in the lower right-hand corner.<sup>5</sup>

Hope this helps.

SEK

---

**From:** Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Sent:** Thursday, May 15, 2025 5:18 PM

**To:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>

**Cc:** Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>

**Subject:** Ch 2

Hi all,

I had a few questions about Chapter 2 (in bubbles in the attached document). My goal is to read closely and comment on every chapter before you guys have your marathon walk-through call. Excellent job on this--I didn't realize how strong the effect of CO<sub>2</sub> was on crop water productivity.

Best,

Travis

---

**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/15/2025 10:39:26 PM  
**To:** 'Judith Curry' [curry.judith@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**CC:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'John Christy' [climatemanager60@gmail.com]  
**Subject:** RE: Ch 2  
**Attachments:** ~WRD1936.jpg

Agreed. Seems a bit snarky.

SEK

---

**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Thursday, May 15, 2025 5:46 PM  
**To:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Cc:** Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climatemanager60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>  
**Subject:** Re: Ch 2

Thanks travis, i agree with you that we need to tone down the rhetoric on section 2.3

On Thu, May 15, 2025 at 2:18 PM Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Thursday, May 15, 2025 6:33 PM  
**To:** 'Travis Fisher'; 'Ross McKittrick'  
**Cc:** 'Roy W. Spencer'; 'John Christy'; 'Judith Curry'  
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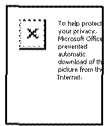
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**Sent:** 5/15/2025 9:18:20 PM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]  
**CC:** Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climateman60@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Judith Curry [curry.judith@gmail.com]  
**Subject:** Ch 2  
**Attachments:** 2 CO2 and greening.May15.docx

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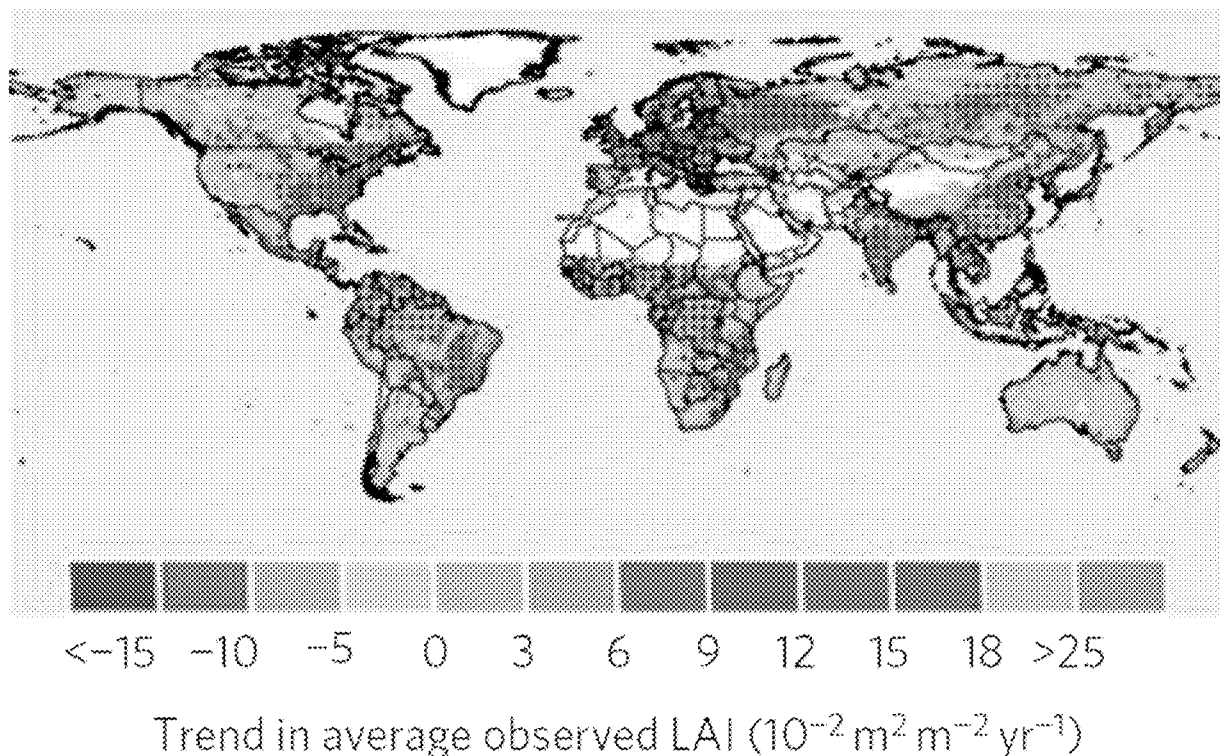
Best,  
Travis

## 2 CO<sub>2</sub> fertilization and global greening

The growing CO<sub>2</sub> concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the “global greening” phenomenon discussed below, as well as in the improving agricultural yields discussed in Chapter 10.

### 2.1 CO<sub>2</sub> and global greening

“Greening” refers to an increase in the fraction of the Earth’s surface covered by plants. It can be quantified by the “Leaf Area Index” (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO<sub>2</sub> levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50% of the Earth versus “browning” over only 4%, and attributed 70% of the greening to rising CO<sub>2</sub> levels (see Figure 2.1).



**Figure 2.1:** Trends in average Leaf Area Index (LAI). Source: Zhu et al. 2016 Figure 3.

Zheng (2017) confirmed the pattern, noting that greening over thirty years had added 8% to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen et al. (2019) noted that China and India were exploiting it though land management changes. Thus while China accounts for only 6.6% of global vegetated area it accounts for 25% of global net increase in LAI. Piao et al. (2020) noted that greening was even observable in the Arctic.

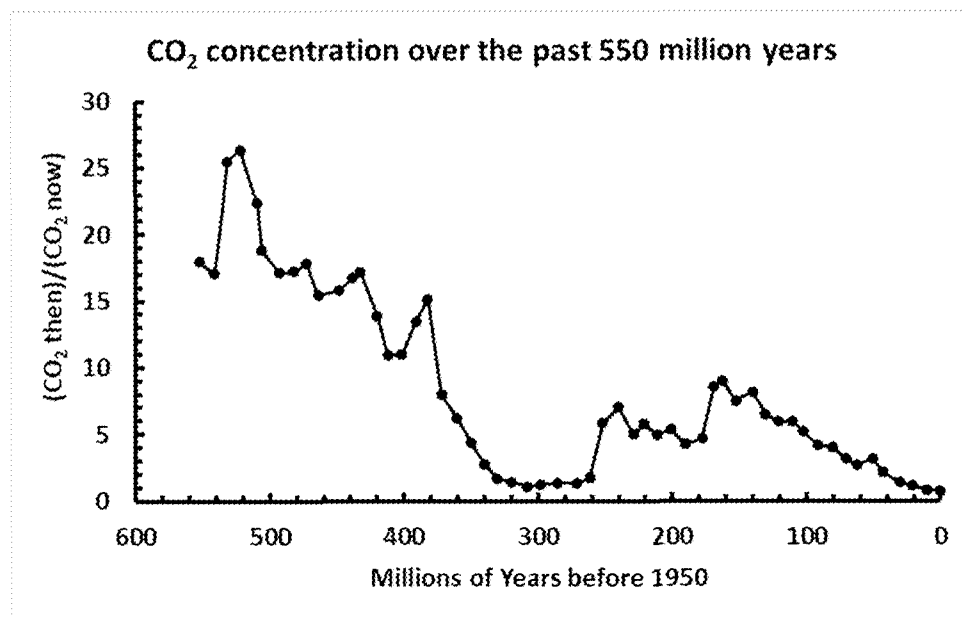
While plant models predict increases in photosynthesis in response to rising CO<sub>2</sub>, Haverd et al. (2020) reported a CO<sub>2</sub> fertilization rate nearly double what models had predicted. That is, CO<sub>2</sub> fertilization had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO<sub>2</sub> have likely understated the benefits to crops and agriculture. The connection between CO<sub>2</sub> fertilization and climate policy will be discussed in Chapter 10.

Finally, Chen et al. surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55% of the globe while browning was accelerating over only 7%. In other words, the greening trend continued with no evidence of slowdown, and CO<sub>2</sub> fertilization remained the dominant driver.

## 2.2 Photosynthesis and CO<sub>2</sub> levels

Plants build biomass through *photosynthesis*, a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is called Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO<sub>2</sub> is available at the surface of the RuBisCo enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the “C3” process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO<sub>2</sub> levels were usually many times higher than they are today, as shown in Figure 2.2



**Figure 2.2.** Ambient CO<sub>2</sub> levels over the past 550 million years as a multiple of current levels.  
Source: Berner (2006)

About 400 million years ago CO<sub>2</sub> levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd et al. 2024).

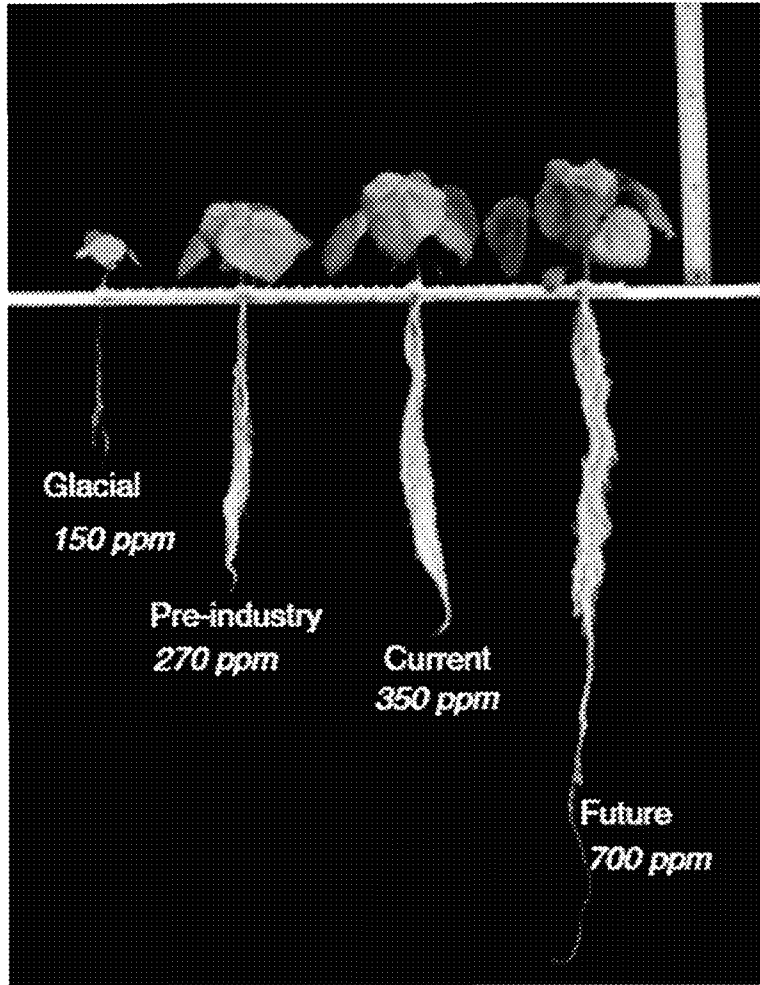
Over the past 35 million years the level of atmospheric CO<sub>2</sub> has been steadily declining. During glaciations levels have fallen as low as 170 ppm (Gerhart and Ward 2010).

In response to low-CO<sub>2</sub> conditions some plants evolved another photosynthetic pathway called C4, in which CO<sub>2</sub> is concentrated in the vicinity of Rubisco allowing for the C3 process to function more efficiently. For agricultural purposes the plant categories are:

- C3: rice, wheat, soybeans and most other crops
- C4: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO<sub>2</sub> levels continued declining, plant growth rates would have declined and eventually ceased. Below 180 ppm many C3 species experience growth rate reductions on the order of 40-60% compared to their growth rates at 350 ppm (Gerhart and Ward 2010). C3 plants have been observed under experimental conditions to stop growing altogether at levels between 60—140 ppm CO<sub>2</sub>. Some C4 plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Currently, CO<sub>2</sub> levels are about 420 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO<sub>2</sub> is illustrated in Figure 2.3 which is reproduced from Gerhart and Ward (2010). It shows the growth effect of CO<sub>2</sub> on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO<sub>2</sub> exposure is varied. The gains exhibited from increasing CO<sub>2</sub> from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.



**Figure 2.3:** growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO<sub>2</sub> levels. Source: Gerhart and Ward (2010).

Over the past 60+ years there have been thousands of studies on the response of plants to rising CO<sub>2</sub> levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO<sub>2</sub>. There are two mechanisms by which CO<sub>2</sub> confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO<sub>2</sub> by opening the stomata (pores) on the leaf surface. When CO<sub>2</sub> is scarce the stomata must be kept wide open for long periods, which allows water to evaporate away. Under enriched CO<sub>2</sub> conditions the stomata are closed for longer periods helping the plant retain water longer, thereby increasing water use efficiency.

Specific effects of climate change on US agriculture will be reviewed in Chapter 10.

*Rising CO<sub>2</sub> and crop water use efficiency*

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO<sub>2</sub> Enrichment—see Chapter 10) on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them so that all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

Similarly, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

### **2.3 Concealment of CO<sub>2</sub> fertilization benefits in IPCC Reports**

If CO<sub>2</sub> emissions had been discovered to be causing global crop declines and regional browning, that surely would have been discussed prominently in IPCC reports, perhaps even with its own chapter in an Assessment Report if not an IPCC Special Report. By contrast the IPCC has been almost silent on the topic of global greening and CO<sub>2</sub> fertilization of agricultural crops.

The topic is briefly acknowledged in a few places in the body of the IPCC 6<sup>th</sup> and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report entitled “global greening and browning” points out that the IPCC Special Report on Climate Change and Land had concluded with *high confidence* that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO<sub>2</sub> fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries and Synthesis Reports conspicuously fail to discuss the topic.

### **References**

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- Judd, Emily et al. (2024) A 485-million-year history of Earth's surface temperature. *Science* 385 Issue 6715 <https://doi.org/10.1126/science.adk3705>
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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 20, 2025 9:48 AM  
**To:** Steven Koonin  
**Cc:** Ross McKittrick; John Christy; Roy Spencer; Travis Fisher  
**Subject:** Re: Albedo text for ch 5

thx i'm good with this

On Tue, May 20, 2025 at 5:47 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

My suggested edits attached.

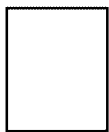
SEK

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**From:** Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Sent:** Monday, May 19, 2025 7:30 PM  
**To:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** Albedo text for ch 5

Attached

--



Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
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<http://www.cfanclimate.net>

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To help protect  
your privacy,  
Microsoft Office  
prevented  
automatic  
download of this  
picture from the  
Internet.

Judith Curry, President  
CFAN - Climate Forecast Applications Network  
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<http://www.cfanclimate.net>

---

**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/20/2025 12:47:40 PM  
**To:** 'Judith Curry' [curry.judith@gmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'John Christy' [climateman60@gmail.com]; 'Roy Spencer' [roywspencer@hotmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** RE: Albedo text for ch 5  
**Attachments:** ~WRD3660.jpg; Hemispheric symmetry of the planetary albedo[SK].docx

My suggested edits attached.

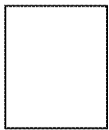
SEK

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Monday, May 19, 2025 7:30 PM  
**To:** Ross McKittrick <ross.mckittrick@gmail.com>; Steve Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Albedo text for ch 5

Attached

--



Judith Curry, President  
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Reno, NV USA  
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<http://www.cfanclimate.net>

## 5.8 Hemispheric symmetry of the Earth's albedo

The planetary albedo is the fraction of solar radiation reflected by the Earth back to space, and is an important component of the radiative balance and hence whether the planet will warm or cool over time. An intriguing property of the Earth's albedo is that, on average, the Northern Hemisphere (NH) and Southern Hemisphere (SH) have had very nearly the same albedo, at least throughout the fifty-year satellite record (Stephens et al., 2015). This symmetry is surprising, because the SH has much more ocean than land. Since ocean is less reflective than land, the NH should have higher albedo. Clouds (which are highly reflective) are more common in the NH, and so compensate the surface albedo imbalances of the two hemispheres. Datseris and Stephens (2021) show that this cloud compensation comes from the extra-tropical storm tracks of the SH, which are cloudier than those of the NH. While the mechanism for this hemispheric symmetry is unclear, it likely operates on large temporal and spatial scales.

The hemispheric symmetry of the albedo is a simple gross metric for climate models. Rugenstein and Hakuba (2023) defined that metric as the difference between the NH and SH annual mean albedos, expressed as  $\text{Wm}^{-2}$  of the reflected sunlight, and compiled it for the CMIP6 climate models, as shown in Figure 5.8.1. Most of the CMIP6 models do not reproduce the small observed asymmetry (about  $0.1 \text{ Wm}^{-2}$ ) and even disagree as to which hemisphere is more reflective. Moreover, the magnitude of the asymmetry ranges up to  $5 \text{ Wm}^{-2}$  in some models, twice as large as the current anthropogenic forcing (about  $2.5 \text{ Wm}^{-2}$ ).

The significance of unphysical albedo asymmetries in the climate models is not yet fully known. However, other model studies suggest that interhemispheric changes in albedo can alter poleward heat fluxes, meridional temperature gradients, storminess, and differences in hemispheric ocean heat storage. The discrepancy between models and observations further raises issues regarding cloud feedback processes and so more generally diminishes confidence in model projections of the future climate.

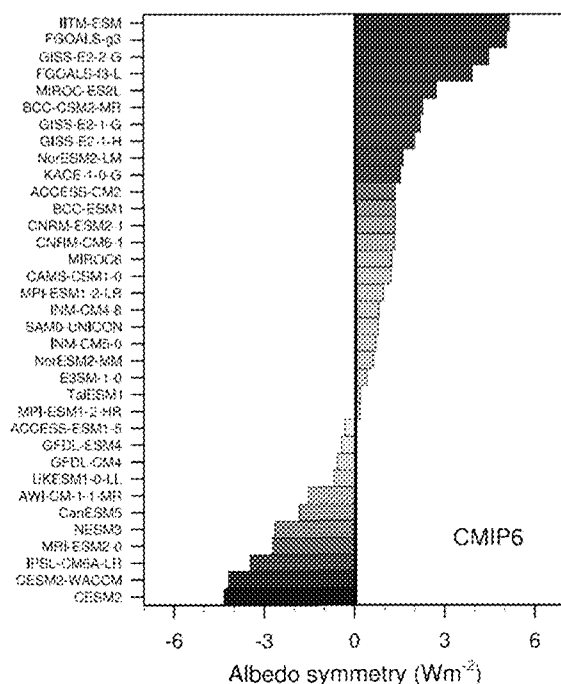


Figure 5.8.1 Differences in the reflectivity (albedo) between the Northern and Southern Hemispheres for CMIP6 models used in the most recent IPCC assessment (colored bars). The very small observed difference is indicated by the vertical black line. From Rugenstein and Hakuba (2023).

Rugenstein, M., & Hakuba, M. (2023). Connecting hemispheric asymmetries of planetary albedo and surface temperature. *Geophysical Research Letters*, 50, e2022GL101802.

Datseris, G., & Stevens, B. (2021). Earth's albedo and its symmetry. *AGU Advances*, 2, e2021AV000440. <https://doi.org/10.1029/2021AV000440>

Stephens, GL, D O'Brian, PJ Webster et al (2015) The albedo of Earth. *Reviews of Geophysics*.

---

**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Monday, May 19, 2025 10:25 PM  
**To:** Judith Curry  
**Cc:** Steve Koonin; John Christy; Roy Spencer; Travis Fisher  
**Subject:** Re: Albedo text for ch 5

Thanks Judy.

On Mon, May 19, 2025 at 7:30 PM Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:  
Attached

--



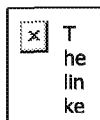
Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

---

**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/19/2025 11:30:12 PM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]; Steve Koonin [steven.koonin@gmail.com]; John Christy [climateman60@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Albedo text for ch 5  
**Attachments:** Hemispheric symmetry of the planetary albedo.docx

Attached

--



Judith Curry, President  
CFAN - Climate Forecast Applications Network  
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<http://www.cfanclimate.net>

## 5.8 Hemispheric symmetry of the planetary albedo

The planetary albedo is the portion of solar radiation reflected by the planet back to space, and is an important determinant of whether the planet will warm or cool over time. An intriguing property of the planetary albedo is that, on average, Northern Hemisphere (NH) and Southern Hemisphere (SH) have the same albedo (Stephens et al., 2015). The hemispheric symmetry is at least robust throughout the satellite record (since the 1970s). The symmetry of the hemispheric albedo is surprising, because SH has much more ocean than land, and ocean is less reflective than land, so the NH should have higher albedo. Clouds (which are highly reflective) compensate the surface albedo imbalances of the two hemispheres, leading to an overall symmetric albedo between the hemispheres. Datseris and Stephens (2021) show that this cloud compensation comes from the extra-tropical storm tracks of the SH, which are cloudier than those of the NH.

While the reasons for this hemispheric symmetry in albedo are unclear, its mechanism likely operates on large temporal and spatial scales. The existence of this symmetry is a useful metric for evaluating climate models. Rugenstein and Hakuba (2023) evaluate the hemispheric albedo for the CMIP6 climate model simulations. Albedo asymmetry is defined by the NH minus the SH the Northern Hemisphere (NH) minus Southern Hemisphere (SH) difference in annual mean hemispheric albedo. The observed asymmetry is small, about  $0.1 \text{ W m}^{-2}$ . Figure 5.8.1 shows that the observed hemispheric symmetry of reflected flux is not reproduced by most of the CMIP6 models, and there is disagreement between models as to which hemisphere is more reflective. The magnitude of the asymmetry in some of the models is very large, compared both to the observed value and to current human influences (about  $2.5 \text{ W m}^{-2}$ ).

The significance of this discrepancy between climate models and observations of the hemispheric albedo symmetry is not yet fully known. However, model studies suggest that interhemispheric changes in albedo can alter the amount of heat moved poleward, meridional temperature gradients, storminess, and differences in hemispheric ocean heat storage. The discrepancy further raises issues regarding cloud feedback processes and their magnitude.

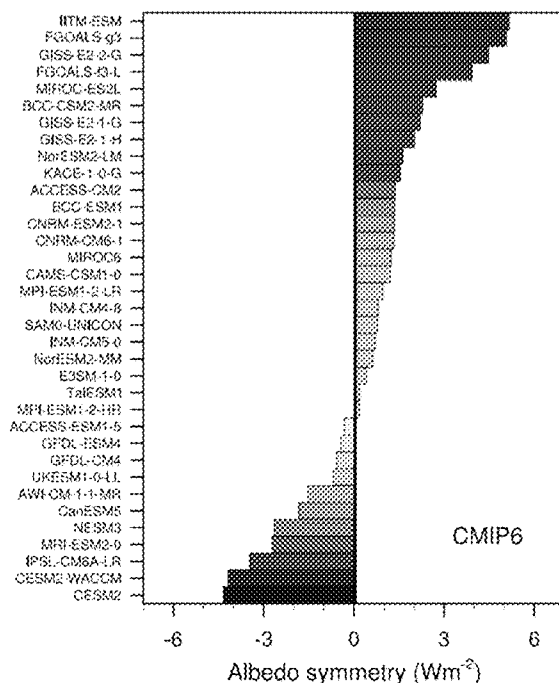




Figure 5.8.1 Differences in the reflectivity (albedo) between the Northern and Southern Hemispheres for CMIP6 models used in the most recent IPCC assessment (colored bars). The very small observed difference is indicated by the vertical black line. From Rugenstein and Hakuba (2023).

Rugenstein, M., & Hakuba, M. (2023). Connecting hemispheric asymmetries of planetary albedo and surface temperature. *Geophysical Research Letters*, 50, e2022GL101802.

Datseris, G., & Stevens, B. (2021). Earth's albedo and its symmetry. *AGU Advances*, 2, e2021AV000440. <https://doi.org/10.1029/2021AV000440>

Stephens, GL, D O'Brian, PJ Webster et al (2015) The albedo of Earth. *Reviews of Geophysics*.

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 20, 2025 10:30 AM  
**To:** Roy Spencer  
**Cc:** Ross McKittrick; Steve Koonin; John Christy; Travis Fisher  
**Subject:** new 3.3.2  
**Attachments:** 3.3.2 curry.docx

ne

On Tue, May 20, 2025 at 4:34 AM Roy Spencer <roywspencer@hotmail.com> wrote:  
...into the carbon cycle chapter where appropriate. As Judy pointed out, there are large variations among models. I will do the ocean models next.

--



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### 3.3.2 The carbon cycle relating emissions and concentrations

Reservoirs of carbon in the earth system include the atmosphere, land ecosystems, the ocean, sediments and the Earth's interior. Excluding rocks, by far the largest reservoir of carbon is the ocean. Exchanges of carbon between reservoirs occurs via various chemical, physical, geological and biological processes. These exchanges establish a dynamical equilibrium over time in the absence of large external perturbations to the system. Since the advent of agriculture, humans have gradually influenced the carbon cycle by modifying the vegetation in land ecosystems. Since the industrial revolution, humans have modified the carbon cycle via production and burning of fossil fuels that emit CO<sub>2</sub> and other carbon-based pollutants into the atmosphere.<sup>i</sup>

Removal of carbon from the atmosphere is achieved via photosynthesis into leaves, roots, stems, and woody biomass. Carbon is returned to the atmosphere through the respiration of plants and the decomposition of plant detritus or dead organic material and also via soil carbon. Disturbances such as fire, insect outbreaks and timber harvesting provide substantial local perturbations to the land-atmosphere carbon exchange. In oceanic regions of ocean upwelling with nutrient-rich warm waters, carbon is outgassed into the atmosphere. By contrast, where there is cold, sinking water, such as in the North Atlantic and Southern Ocean, carbon is removed from the atmosphere. Carbon is exchanged between land and ocean reservoirs via river transport from interior regions to the coastal ocean.<sup>ii</sup>

The El Niño Southern Oscillation (ENSO) is a significant driver of tropical carbon flux variability for both the ocean and terrestrial ecosystems. During the warm phase of ENSO (El Niño), the ocean takes up more carbon because of reduced upwelling and outgassing from the eastern Tropical Pacific. On land, El Niño is associated with drought and warmer temperatures, resulting in outgassing from land ecosystems. There is also substantial decadal variability in the land and ocean carbon sinks, driven by atmospheric and oceanic circulation patterns in the extratropics.<sup>iii</sup>

The annual estimation of global CO<sub>2</sub> emissions and sinks is a major effort by the international carbon cycle research community that includes compilation and synthesis of measurements, statistical estimates, and model results. The ocean CO<sub>2</sub> sink showed rapid growth during the past decade, after little to no growth during 1991–2002. The land CO<sub>2</sub> sink demonstrated a continued increase during the last decade (2011–20), driven predominantly by increased atmospheric CO<sub>2</sub>.<sup>iv</sup>

While there is good qualitative understanding of the relevant processes involved in the global carbon cycle, our quantitative understanding is relatively weak.<sup>v</sup> There is persistent large uncertainty in the estimate of CO<sub>2</sub> fluxes from land-use changes. There is low agreement between the varied methods with respect to the magnitude of the land CO<sub>2</sub> flux in the northern extra-tropics. There is also substantial discrepancy between the different methods on the strength of the ocean sink over the last decade, particularly in the Southern Ocean.<sup>vi</sup> There is also concern about permafrost feedback loops, that could release more carbon into the atmosphere with warming.

Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that exchange CO<sub>2</sub> with the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO<sub>2</sub> in and out of the Earth's surface are an order of magnitude larger than anthropogenic emissions, but the natural CO<sub>2</sub> sources and sinks were assumed to be in approximate balance in pre-industrial times, as inferred from relatively constant levels of atmospheric CO<sub>2</sub> found in air bubbles trapped in ice cores. This is one of several reasons why increasing atmospheric CO<sub>2</sub> levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO<sub>2</sub> levels in the atmosphere, as shown in Fig. 3.1.3. CO<sub>2</sub> emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO<sub>2</sub>. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al. 2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

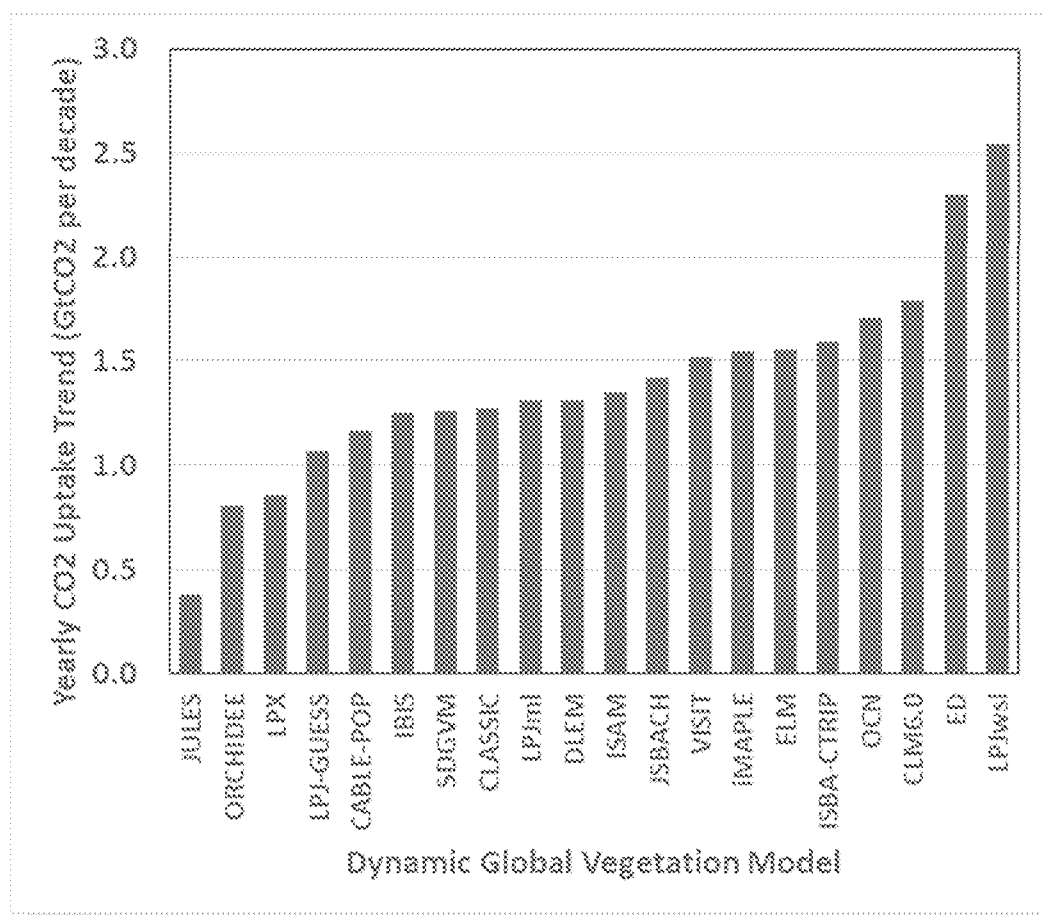
As noted, each year natural processes remove a net amount of CO<sub>2</sub> equivalent to about 50% of global emissions. Thus, anthropogenic CO<sub>2</sub> emissions average twice what is required to explain the atmospheric rise in CO<sub>2</sub> concentration. The historical near-constancy of that 50% fraction also means that the more CO<sub>2</sub> humanity has produced, the faster Nature removed it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO<sub>2</sub> after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes that remove excess CO<sub>2</sub> from the atmosphere are increased growth of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO<sub>2</sub> by the ocean due to the increasing partial pressure of atmospheric CO<sub>2</sub> over that of CO<sub>2</sub> dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO<sub>2</sub> at an increasing rate since 1959. This is consistent with a “global greening” phenomenon (Chapter 2.1) observed by satellites since monitoring of global greenness began in the 1982.

While land vegetation has been responding positively to more atmospheric CO<sub>2</sub>, uptake of extra CO<sub>2</sub> by ocean biological processes remains too uncertain to be measured reliably. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp *et al.* (2021).

#### *CO<sub>2</sub> uptake by land processes*

The uptake of extra CO<sub>2</sub> from the atmosphere by land surface processes (as also inferred from global greening) has been modeled with 20 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). As seen in Fig. 3.3.3, all of those models agree that vegetation and soils have been sequestering carbon from the atmosphere. But we also see that the long-term trends over 1959 to 2023 (65 years) vary widely between models, by nearly a factor of 7. This demonstrates that there remains considerable uncertainty regarding how fast CO<sub>2</sub> from the atmosphere is being removed by land processes, which in turn translates into uncertainty regarding future atmospheric CO<sub>2</sub> concentrations. Those uncertain future CO<sub>2</sub> concentrations then imply a source of uncertainty in climate model simulations of future climate change.

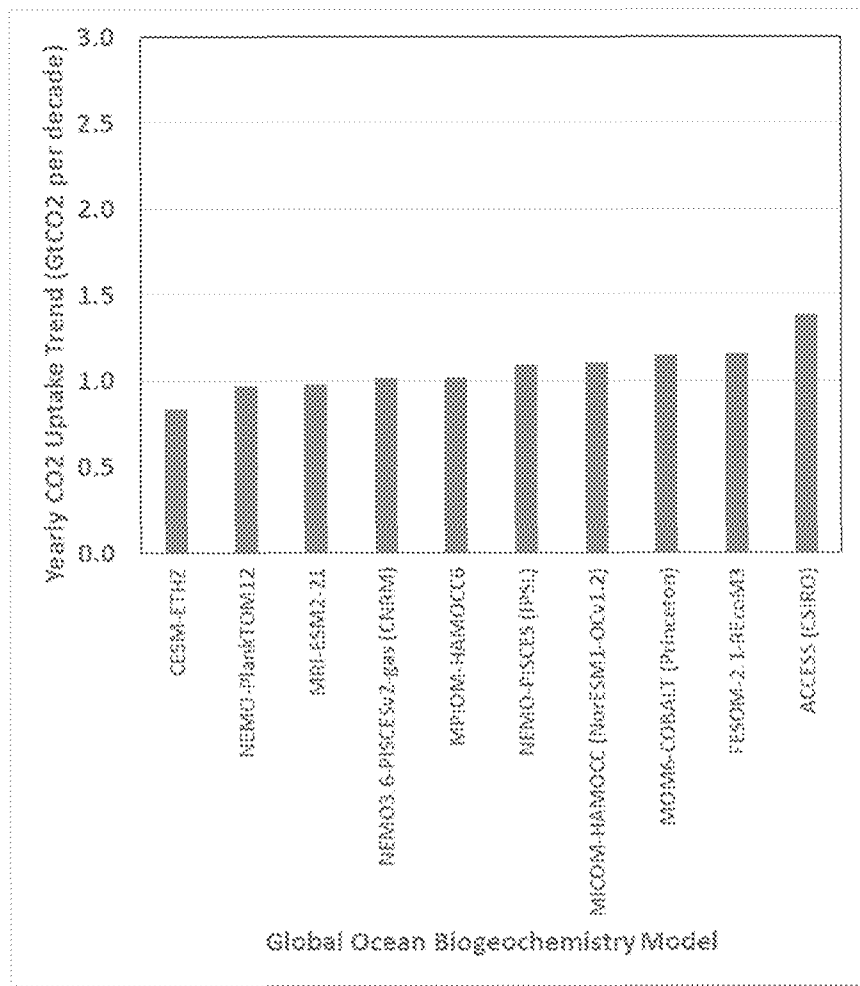


**Figure 3.3.3** Decadal trends in the yearly CO<sub>2</sub> uptake by land processes during 1959-2023 simulated by 20 different dynamic global vegetation models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

#### *CO<sub>2</sub> uptake by ocean processes*

The uptake of extra CO<sub>2</sub> from the atmosphere by ocean processes has been modeled with 10 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). Like the results from the land models, all of the ocean models agree that the global oceans have been sequestering carbon from the atmosphere at an increasing rate during 1959-2023 (Fig. 3.3.4). Unlike the land models, however, the ocean models show much better agreement with each other, with the model producing the fastest increasing CO<sub>2</sub> uptake being only 65% faster than the model with the most slowly increasing CO<sub>2</sub> uptake. Note that the average trend in CO<sub>2</sub> uptake across all land models in Fig. 3.3.3 is 25% larger than the average trend in ocean uptake. This suggests land

processes are increasing in their ability to remove CO<sub>2</sub> faster than ocean processes are increasing their CO<sub>2</sub> sequestration.



**Figure 3.3.5** Decadal trends in the yearly CO<sub>2</sub> uptake by ocean processes during 1959-2023 simulated by 10 different ocean biogeochemistry models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

New research continues to provide surprises. Phytoplankton, which live on the warm, light-filled ocean surface, use atmospheric CO<sub>2</sub> for food. Phytoplankton sequester carbon and once they die and sink, carry it to the ocean depths. A recent study found evidence that phytoplankton may become more efficient at sequestering carbon as the ocean warms. Another recent article reported the discovery of a widely circulated microbe variety that demonstrates the potential to sequester carbon.<sup>vii</sup>

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<sup>i</sup> “Chapter 1: Overview of the Global Carbon Cycle,” Second State of the Carbon Cycle Report (U.S. Global Change Research Program), accessed July 25, 2022, <https://carbon2018.globalchange.gov/chapter/1/>.

<sup>ii</sup> Ibid.

<sup>iii</sup> Peter Landschützer et al., “Decadal Variations and Trends of the Global Ocean Carbon Sink,” *Global Biogeochemical Cycles* 30, no. 10 (October 5, 2016): 1396-1417, <https://doi.org/10.1002/2015gb005359>.

<sup>iv</sup> Pierre Friedlingstein et al., “Global Carbon Budget 2021,” *Earth System Science Data* 14, no. 4 (April 26, 2022): 1917-2005, <https://doi.org/10.5194/essd-14-1917-2022>.

<sup>v</sup> Ibid.

<sup>vi</sup> Ibid.

<sup>vii</sup> Nancy Averett, “The Ocean Is Still Sucking up Carbon-Maybe More than We Think,” *Eos*, May 3, 2022, <https://eos.org/articles/the-ocean-is-still-sucking-up-carbon-maybe-more-than-we-think>.



---

**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/19/2025 8:04:50 PM  
**To:** 'Roy Spencer' [roywspencer@hotmail.com]; 'Judith Curry' [curry.judith@gmail.com]  
**CC:** 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Ross McKittrick' [ross.mckitrick@gmail.com]; 'John Christy' [climateman60@gmail.com]  
**Subject:** RE: Why are our conclusions so different from those in 2009?  
**Attachments:** ~WRD1987.jpg

I think another purpose of our report is to counter the climate misinformation that's so pervasive. Per Mark Twain:

'It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so.'

---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Monday, May 19, 2025 3:20 PM  
**To:** Judith Curry <curry.judith@gmail.com>  
**Cc:** Travis Fisher <travis.scott.fisher@gmail.com>; Ross McKittrick <ross.mckitrick@gmail.com>; John Christy <climateman60@gmail.com>; Steve Koonin <steven.koonin@gmail.com>  
**Subject:** RE: Why are our conclusions so different from those in 2009?

The report isn't "about sound bites". It's full of detail. The issue is summarizing the most overarching conclusions in a way that (1) everyone can understand, and (2) people might actually read (few will read the report).

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

**From:** Judith Curry <curry.judith@gmail.com>  
**Date:** 5/19/25 2:15 PM (GMT-06:00)  
**To:** Roy Spencer <roywspencer@hotmail.com>  
**Cc:** Travis Fisher <travis.scott.fisher@gmail.com>, Ross McKittrick <ross.mckitrick@gmail.com>, John Christy <climateman60@gmail.com>, Steve Koonin <steven.koonin@gmail.com>  
**Subject:** Re: Why are our conclusions so different from those in 2009?

I don't want this report to be about media sound bites. Lets just focus on a clear scientific presentation that is policy relevant

On Mon, May 19, 2025 at 7:36 AM Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)> wrote:

I understand the desire for a diplomatic tone, but if you want media outlets to take away details from the report, it will need to be easily understood sound bites, summarizing the major conclusions. I feel like that is still missing from what Ross suggested.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

Date: 5/19/25 9:27 AM (GMT-06:00)

To: Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>

Cc: Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>, John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>, Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>, Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>

Subject: Re: Why are our conclusions so different from those in 2009?

This would be a very helpful addition (especially if you use a diplomatic tone--I like Ross's tone here).

For today's meeting, please consider me "on call" if anything comes up that you'd like me to be present for. Otherwise, I'll wait to see the results and try to format quickly behind you all.

If there are chapters that you all feel are close enough to final to be formatted and included in a single document, please let me know, and I can do that while you continue to discuss other chapters.

On Mon, May 19, 2025 at 10:09 AM Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:

Perhaps as part of the introduction a paragraph along these lines:

In this report we have taken prior assessments by groups like the IPCC and NCA as starting points, and in many cases our conclusions are either the same as theirs or where they offer a range of plausible conclusions we fall within that range. In some places, however, we differ from the IPCC or NCA. In those cases we have gone into some detail to explain the basis of our disagreement. Occasionally we find prior assessments have paid insufficient attention to contrary evidence, and in other cases new research has emerged since earlier assessments that challenges earlier conclusions. In one case, the topic of CO2 fertilization and global greening, we find the IPCC and the NCA have been almost completely silent so we cannot compare our findings to theirs.

I'd like to make it as non-combative as possible and to emphasize for readers that in fact we are positioned well within the mainstream. Some of our critics will be the ones out on the margins.

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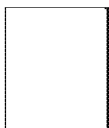
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**Subject:** RE: Why are our conclusions so different from those in 2009?

The report isn't "about sound bites". It's full of detail. The issue is summarizing the most overarching conclusions in a way that (1) everyone can understand, and (2) people might actually read (few will read the report).

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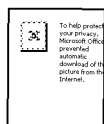
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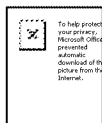
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From: Travis Fisher <travis.scott.fisher@gmail.com>  
Date: 5/19/25 9:27 AM (GMT-06:00)  
To: Ross McKittrick <ross.mckittrick@gmail.com>  
Cc: Roy Spencer <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Judith Curry <curry.judith@gmail.com>, Steve Koonin <steven.koonin@gmail.com>  
Subject: Re: Why are our conclusions so different from those in 2009?

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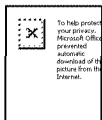
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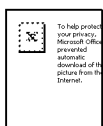
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---

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Monday, May 19, 2025 6:56 AM  
**To:** Roy Spencer  
**Cc:** Ross McKittrick; John Christy; Judith Curry; Travis Fisher  
**Subject:** Re: Why are our conclusions so different from those in 2009?

Roy-

what you've written is a fine start on an Executive Summary.

Steven E. Koonin

On May 19, 2025, at 06:50, Roy Spencer <roywspencer@hotmail.com> wrote:

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**Sent:** Sunday, May 18, 2025 10:39 PM

**To:** John Christy <climateman60@gmail.com>

**Cc:** Judith Curry <curry.judith@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steve Koonin <steven.koonin@gmail.com>

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prevented  
automatic  
download of this  
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**Sent:** Monday, May 19, 2025 6:51 AM  
**To:** Ross McKittrick; John Christy  
**Cc:** Judith Curry; Travis Fisher; Steve Koonin  
**Subject:** Why are our conclusions so different from those in 2009?

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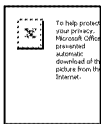
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**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Wednesday, May 21, 2025 10:18 AM  
**To:** Steven Koonin  
**Cc:** Roy Spencer; John Christy; Judith Curry; Travis Fisher  
**Subject:** Re: US tornado writeup, with plots (1950-2024) for the severe weather chapter  
**Attachments:** image001.png

Looks good.

On Wed, May 21, 2025 at 10:12 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

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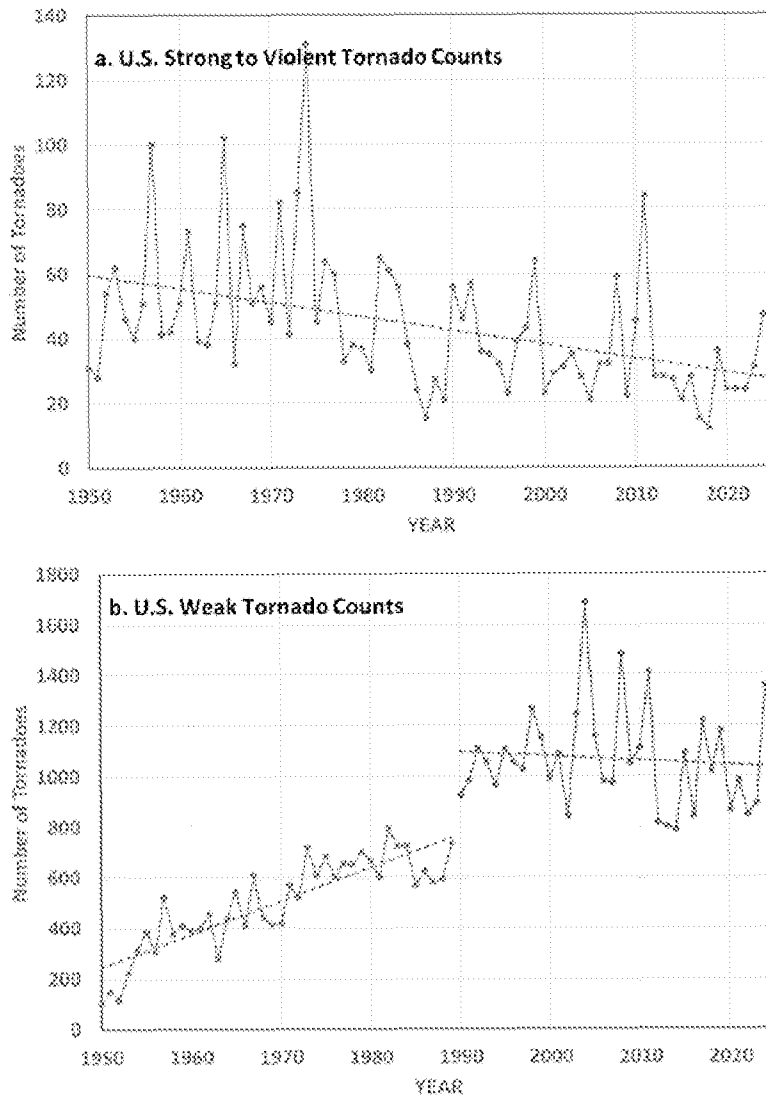
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The monitoring of weak tornadoes has changed over time. The growth of rural population and the increasing ability to take video with hand-held devices as lead to more, and more prominent, observations of weak tornadoes that produce minimal damage. In contrast, strong to violent tornadoes have been observed more consistently over time. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.6.1a. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage, even if the tornado itself was not observed.

The number of observed weak tornadoes (Fig. 6.6.1b) increased from 1950 to 1990, a trend likely due to improved monitoring. There has been no increase after 1990.



**Fig. 6.6.1.** Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms Prediction Center data, available at [https://www.spc.noaa.gov/wcm/data/1950-2024 actual tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)

To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

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**Sent:** Wednesday, May 21, 2025 9:55 AM

**To:** Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>

**Cc:** Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Judith Curry

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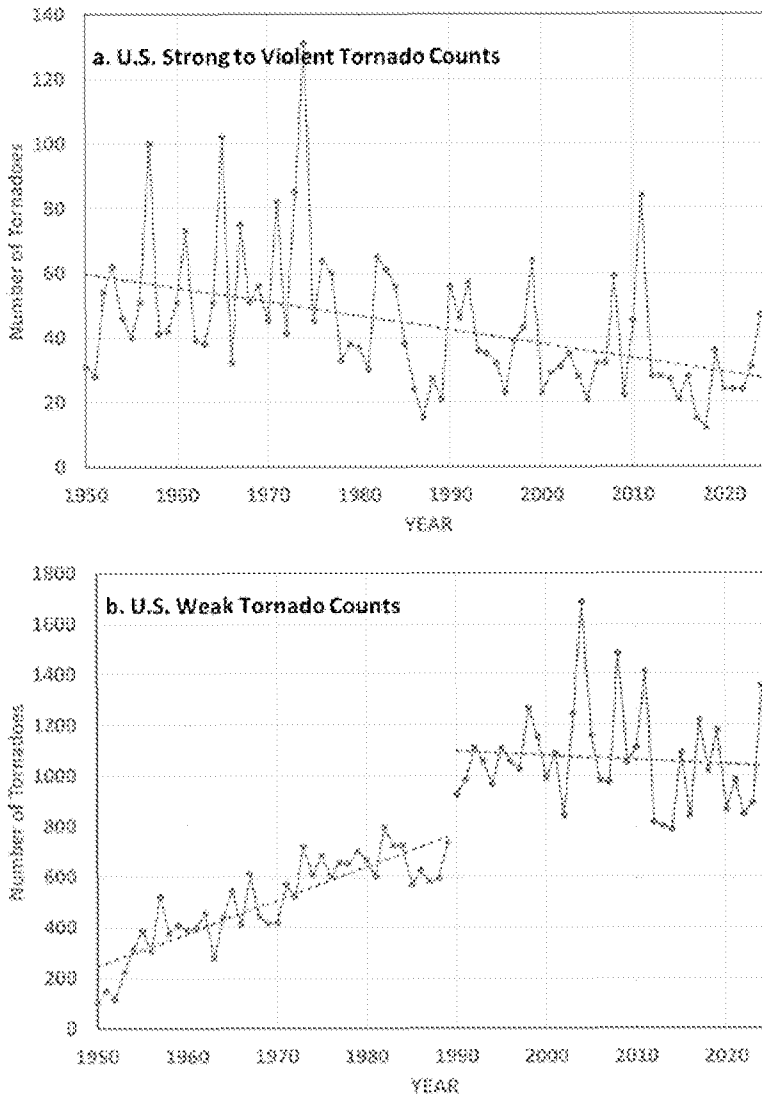
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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/21/2025 2:12:51 PM  
**To:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Roy Spencer' [roywspencer@hotmail.com]  
**CC:** 'John Christy' [climateman60@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
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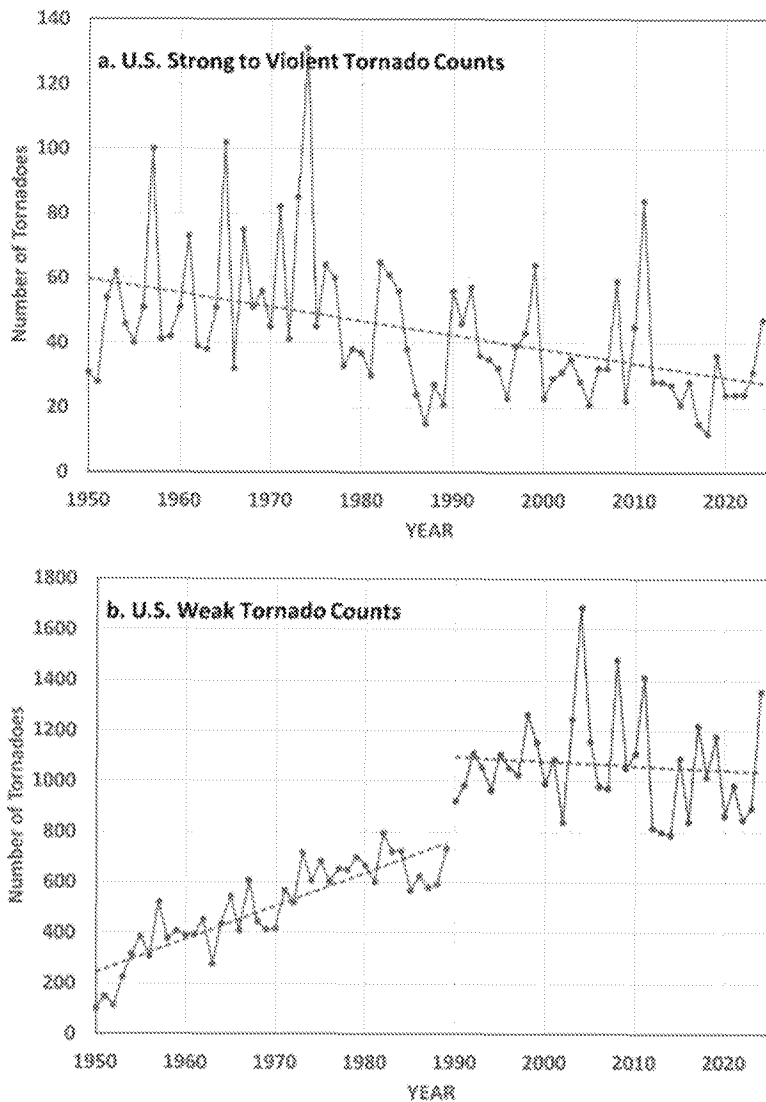


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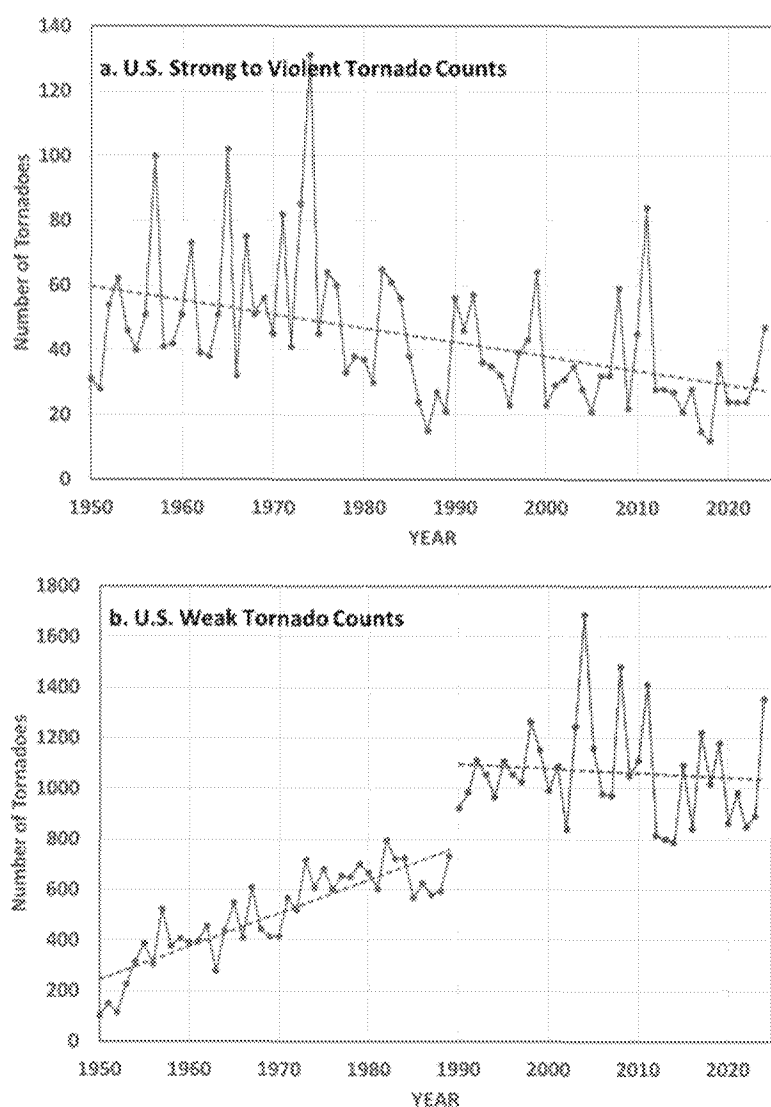


Fig. 6.6.1. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms Prediction Center data, available at [https://www.spc.noaa.gov/wcm/data/1950-2024\\_actual\\_tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)

To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

On Wed, May 21, 2025 at 9:31 AM Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)> wrote:

.....

---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Wednesday, May 21, 2025 10:05 AM  
**To:** Ross McKittrick  
**Subject:** RE: US tornado writeup, with plots (1950-2024) for the severe weather chapter

Looks good to me.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Ross McKittrick <ross.mckittrick@gmail.com>  
Date: 5/21/25 8:55 AM (GMT-06:00)  
To: Roy Spencer <roywspencer@hotmail.com>  
Cc: Steve Koonin <steven.koonin@gmail.com>, John Christy <climateman60@gmail.com>, Judith Curry <curry.judith@gmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>  
Subject: Re: US tornado writeup, with plots (1950-2024) for the severe weather chapter

I integrated it with the IPCC text and rearranged is slightly. Let me know if this is ok:

AR6 assesses tornado trends in the US as follows:

[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

Monitoring of weak tornadoes has changed over time with the spread of the U.S. population into rural areas and the increasing ability to take video with hand-held devices, leading to more opportunities for weak tornadoes producing minimal damage to be observed. Strong to violent tornadoes have been more consistently observed over time. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.6.1a. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage which will be assessed later even if the tornado itself was not observed.

The number of observed weak tornadoes (Fig. 6.6.1b) went up from 1950 to 1990, a trend which is likely due to improved monitoring. After 1990 there has been no increase.

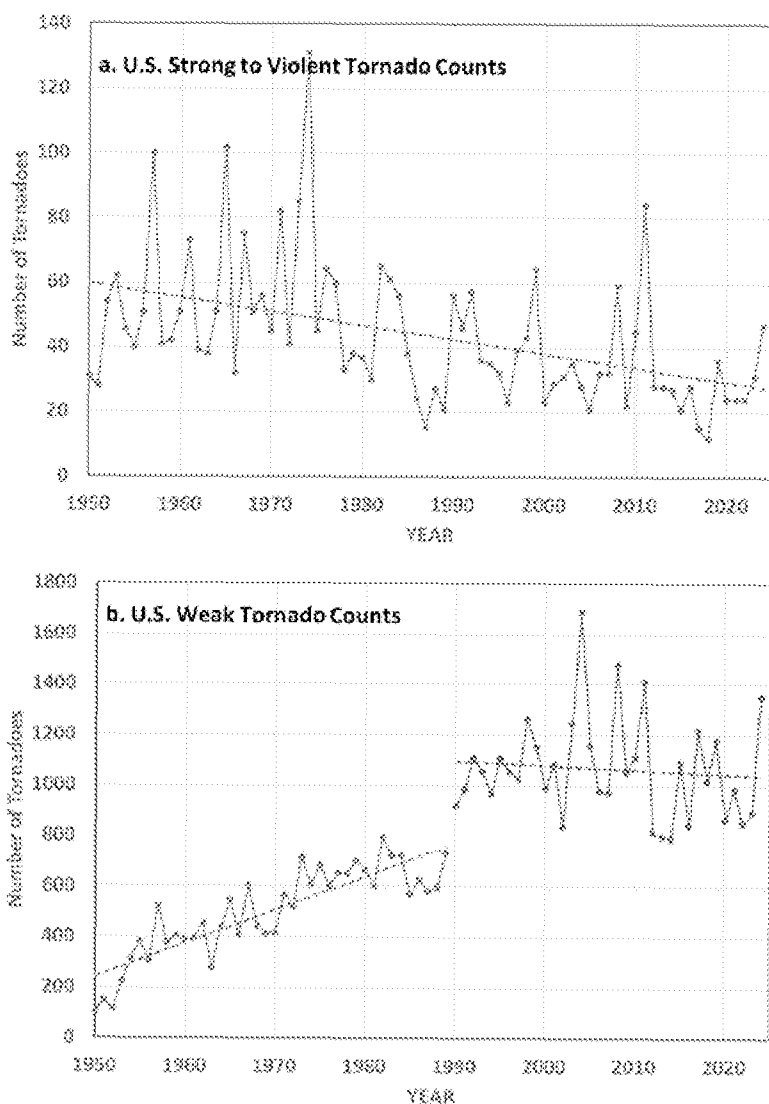


Fig. 6.6.1. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms Prediction Center data, available at [https://www.spc.noaa.gov/wcm/data/1950-2024 actual tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)

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---

**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/21/2025 1:55:12 PM  
**To:** Roy Spencer [roywspencer@hotmail.com]  
**CC:** Steve Koonin [steven.koonin@gmail.com]; John Christy [climateman60@gmail.com]; Judith Curry [curry.judith@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: US tornado writeup, with plots (1950-2024) for the severe weather chapter  
**Attachments:** image.png

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The number of observed weak tornadoes (Fig. 6.6.1b) went up from 1950 to 1990, a trend which is likely due to improved monitoring. After 1990 there has been no increase.

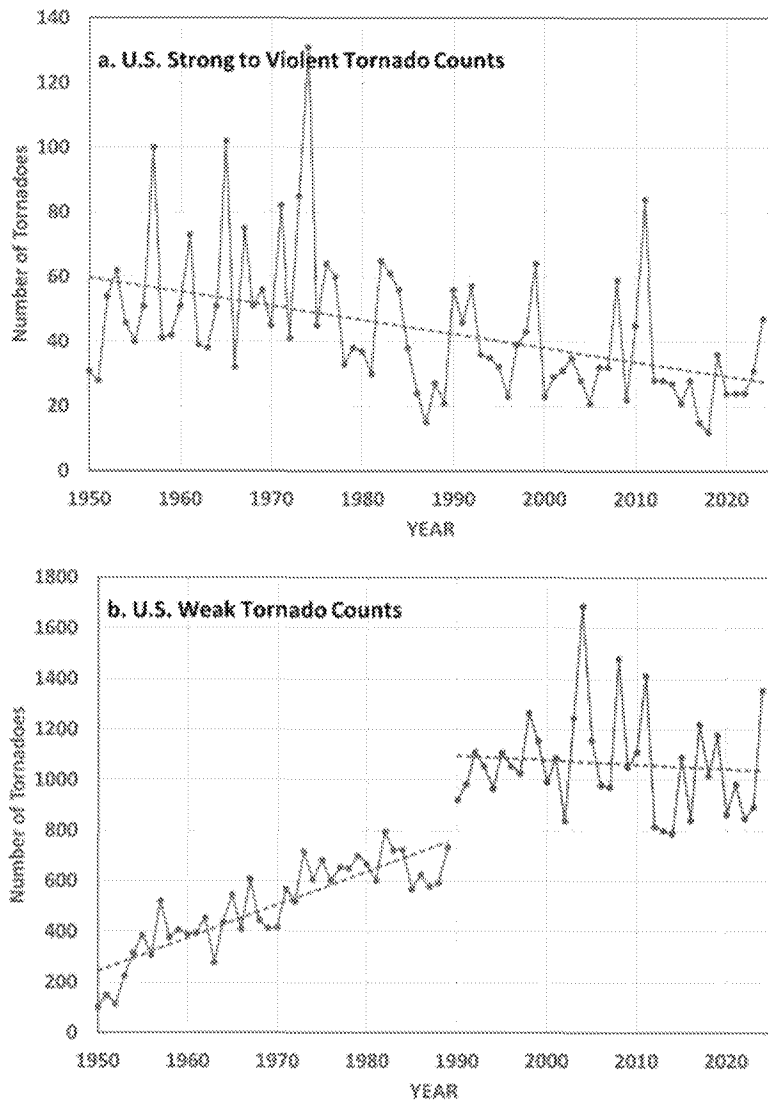


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To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

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---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Wednesday, May 21, 2025 9:32 AM  
**To:** Ross McKittrick  
**Cc:** Steve Koonin; John Christy; Judith Curry; Travis Fisher  
**Subject:** US tornado writeup, with plots (1950-2024) for the severe weather chapter  
**Attachments:** Changes in US tornadoes 1950-2024 [RS].docx

One notable class of US severe weather that has undergone long-term changes is tornadoes. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes 1950-2024, as is shown in Fig. Xa.

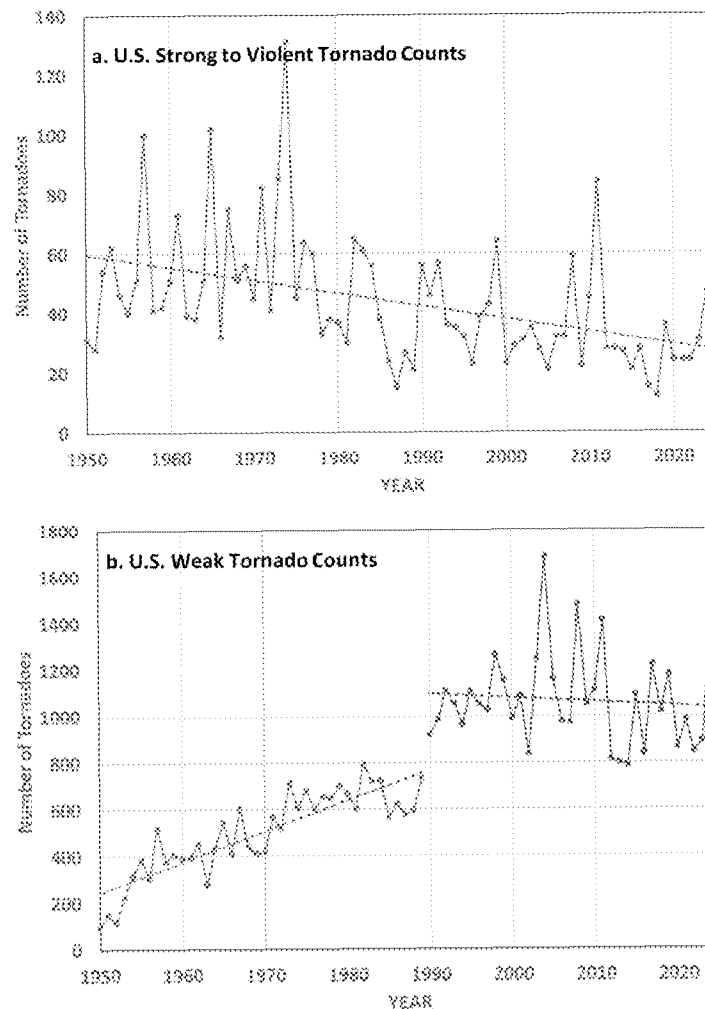


Fig. X. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms Prediction Center data, available at [https://www.spc.noaa.gov/wcm/data/1950-2024\\_actual\\_tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)

The number of weak tornadoes (Fig. Xb) went up from 1950 to 1990, a feature which is likely due to the spread of the U.S. population into what were rural areas, leading to more opportunities for weak tornadoes producing minimal damage to be observed. But between 1990 and 2024 there has been no increase. The reason for the difference is that strong to violent tornadoes leave much more damage which will be noticed later even if the tornado itself is not observed (tornado strength is measured by the damage it produces, not by the visual appearance of the funnel). But the identification of weak tornadoes has been aided by many more people covering a larger area, with increasing ability to take video with cell phones.

---

**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/20/2025 1:05:46 PM  
**To:** 'Judith Curry' [curry.judith@gmail.com]; 'John Christy' [climatemanager60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Roy Spencer' [roywspencer@hotmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]  
**Subject:** revised climate modeling box  
**Attachments:** Rewording of modeling box.docx

Because the current climate modeling box in Chapter 5 reproduces verbatim most of what I'd published in a popular article, I reworded it by editing the results of running it through an LLM.

The new version is attached and should replace the current box.

Steve Koonin

Most climate models, except for the simplest ones, represent Earth's land surface using a grid of squares, typically 100 km wide. To simulate the atmosphere, 10 to 20 layers of grid boxes are stacked above these squares. The ocean is modeled using a similar but finer grid, resulting in approximately one million grid boxes for the atmosphere and 100 million for the ocean.

These models apply fundamental physics to calculate how air, water, and energy move between grid boxes over time. The time step can be as small as 10 minutes, and repeating this process millions of times allows the simulation of climate over centuries. Running these models, even on the most powerful supercomputers, can take months. Comparing simulation results with historical climate data helps assess the accuracy of a model, while projections into the future estimate climate changes under assumed human and natural influences.

Despite sounding straightforward, climate modeling is highly complex. Many critical processes occur at scales smaller than the 100 km grid size. For instance, the flows of sunlight and heat in the atmosphere depend strongly on cloud cover. Since tracking individual clouds is impractical, researchers must make "subgrid" assumptions about the distribution of clouds in each grid box. Snow and ice cover, which affects how much sunlight is reflected or absorbed by the surface, is another subgrid factor.

Each subgrid assumption requires numerical parameters, which must be carefully set. Modelers initially estimate these parameters based on physics and observed climate patterns, then run the model. Because early results often diverge significantly from real-world observations, they "tune" these parameters to better match observed climate features. Different modeling teams use distinct assumptions and tuning strategies, leading to varied outcomes. Tuning is a necessary but delicate aspect of climate modeling, as it is in any complex system. Poor tuning can result in inaccurate simulations, while excessive tuning risks artificially steering results toward predetermined conclusions.

To distill useful insights from these varied models, climate studies often rely on averaged results from multiple models, forming an "ensemble." The latest UN IPCC assessments use the CMIP6 ensemble, which shows a significant diversity of results. One of the most basic climate indicators—the Earth's average surface temperature—varies by about 3°C across the ensemble, three times greater than observed warming during the 20th century.

Although model success in reproducing some features of today's climate is reassuring, the critical issue for society is how well they predict responses to subtle human influences, such as greenhouse gas emissions, aerosol cooling, and land-use changes. The most crucial aspect models must capture correctly is "feedbacks." These occur when climate changes triggered by greenhouse gases either amplify or suppress further warming. For example, as global temperatures rise, snow and ice melt, reducing Earth's reflectivity. With less reflective surfaces,

the planet absorbs more sunlight, leading to additional warming. Other significant feedbacks involve water vapor levels, cloud formation, and atmospheric temperature profiles. Based on ensemble averages, the net effect of all feedbacks is estimated to double or triple the direct warming impact of CO<sub>2</sub>.

---

**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/15/2025 7:44:45 PM  
**To:** Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climateman60@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Judith Curry [curry.judith@gmail.com]  
**Subject:** glossary  
**Attachments:** Glossary.May15.[RM].docx

A few revisions to the Glossary.

## GLOSSARY

**2XCO<sub>2</sub>:** doubling of the atmospheric CO<sub>2</sub> content relative to pre-Industrial times, a commonly used baseline for addressing climate change. In 2025, atmospheric CO<sub>2</sub> concentrations were approximately 50% of the way to 2XCO<sub>2</sub>.

**ABATEMENT:** in the context of environmental policy the reduction of emissions

**ACE (Accumulated Cyclone Energy):** a statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds

**ACIDIFICATION:** a commonly used term for the reduction in ocean pH from more alkaline to less alkaline values

**AEROSOLS:** tiny solid or liquid particles suspended in the air

**ALKALINE:** having a chemical pH greater than 7.0. The "opposite" of acidic, which means a pH less than 7.0

**AMBIENT:** relating to the immediate surroundings of something

**ANTHROPOGENIC:** created by humans

**AR (IPCC Assessment Reports):** periodic assessments published by the IPCC evaluating current knowledge of the climate system, global change, and associated issues. An AR now consists of reports from three working groups, the first (WG1) concerned with physical science. The most recent was the AR6.

**ATTRIBUTION:** assertion of a causal relation, chiefly from anthropogenic GHG emissions to observed climate patterns.

**AUTOCORRELATION:** the phenomenon in which the current value of a random time series variable is correlated with its value in a previous time period.

**BIOMASS:** the total quantity or weight of organic matter in a given area or volume

**CARBON:** The 6<sup>th</sup> element in the periodic table. Popularly used as a shorthand term for carbon dioxide

**CMIP (Coupled Model Intercomparison Project):** The IPCC's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s). The two most recent were the CMIP5 and CMIP6 for, respectively, AR5 and AR6.

**CONUS:** the contiguous 48 U.S. states

**DICE (Dynamic Integrated model of the Climate and Economy):** An Integrated Assessment Model (IAM) developed by William Nordhaus in 1993.

**DISCOUNT RATE:** The interest rate used to convert future costs and benefits of environmental regulations into their present value. Varies inversely with present value so a high discount rate reduces the present value of future costs and benefits.

DRY ICE: frozen carbon dioxide

ECONOMETRICS: the branch of economics concerned with the use of statistical methods (chiefly multiple regression) to analyse economic systems

ECS (Equilibrium Climate Sensitivity): The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO<sub>2</sub> concentration compared to pre-Industrial levels.

EL NIÑO: the warm phase of ENSO, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO<sub>2</sub> uptake by land and ocean.

ENDANGERMENT FINDING (EF): the 2009 finding by the Administrator of the EPA that CO<sub>2</sub> emissions endanger human health and welfare

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean

FACE: (Free-Air CO<sub>2</sub> Enrichment) large-scale open-air studies that expose plants to elevated CO<sub>2</sub> levels, simulating future climate scenarios.

FOSSIL FUEL: a natural hydrocarbon fuel such as coal or natural gas formed in the geological past from the remains of living organisms

FUND: An Integrated Assessment Model (IAM) developed by Richard Tol in 1997.

GBR (Great Barrier Reef): the world's largest coral reef ecosystem located off the northeast coast of Australia

GDP (Gross Domestic Product): total market value of all the final goods and services produced within a country's border, usually over one year

GHCN: the Global Historical Climatology Network, consisting of a time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: the satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s

GNP (Gross National Product): total market value of all the final goods and services produced by the citizens a country, usually over one year

GREENHOUSE EFFECT (GHE): the tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.



GREENHOUSE GAS (GHG): an atmospheric gas that absorbs and emits infrared (IR) radiation, especially water vapor, CO<sub>2</sub>, and methane.

HURST PHENOMENON: see long term persistence.

HYDROLOGY: the study of the movement of water, especially on land and the atmosphere

IAM (Integrated Assessment Model): a computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions

IEA: International Energy Agency

IPCC (Intergovernmental Panel on Climate Change): A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies

IR (Infrared): heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

LA NIÑA: the cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON): a form of autocorrelation in which random fluctuations induce long term but not permanent changes in the mean value of a series, which shows up in some climate data series as cyclical or trending patterns on short time scales

MAIZE: corn

MODEL: a computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes

MORTALITY: death or number of deaths, usually expressed for a specific population and period

NCA (National Climate Assessment): A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States> There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023)

OECD (Organization for Economic Cooperation and Development): a specific list of 38 countries having a democratic system of government and free economic systems

PALEOCLIMATE: climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

PDI (Power Dissipation Index): a statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds

PHOTOSYNTHESIS: the process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function)

PPM: parts per million, a measure of the concentration of a substance in (for example) the atmosphere

PRE-INDUSTRIAL: the historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s

RADIATIVE FEEDBACK: a change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature

RADIATIVE FORCING: the change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

RCP SCENARIOS: Representative Concentration Pathways, different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they assume in 2100 relative to pre-Industrial times, in Watts per sq. meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

REGRESSION: A statistical method for selecting the coefficients of a linear equation to explain the behaviour of a dependent variable in terms of variations in one or more explanatory variables.

RICARDIAN ANALYSIS: a method used in environmental economics named after David Ricardo to estimate the economic impacts of climate change, particularly on agriculture, by making use of the hypothesis that expected changes in the return to future agricultural activity will be capitalized into current land values.

SOCIAL COST OF CARBON (SCC): an estimate of the total economic damages, measured in dollars, caused by emitting one additional ton of CO<sub>2</sub> into the atmosphere

SSP SCENARIOS: Shared Socioeconomic Pathways, different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

TC: tropical cyclone

TMAX: the daily maximum surface air temperature

TMIN: the daily minimum surface air temperature

TOA: top of atmosphere

TOXICOLOGY: the study of the adverse effects of chemical substances on living organisms.

TREND: a coefficient, usually estimated using linear regression, representing the slope of a line of best fit through a time series of data, indicating any tendency for the series mean to move up or down over time.

UHI (Urban Heat Island): the tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

USHCN: the U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations

---

**From:** John Christy <climateman60@gmail.com>  
**Sent:** Tuesday, May 20, 2025 9:05 PM  
**To:** Judith Curry  
**Cc:** Roy Spencer; Steve Koonin; Ross McKittrick; Travis Fisher  
**Subject:** Re: Tornado Emergency

Thanks Judy

As you can imagine it takes a log of budget to deploy our mobile radars and other equipment, so knowing when to pull the trigger on a deployment and where to deploy that stuff would be very cost effective for us.

John C.

John Christy  
Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
climateman60@gmail.com

On May 20, 2025, at 8:00 PM, Judith Curry <curry.judith@gmail.com> wrote:

good verification on the hail. I will send hail and tornado forecasts for this one

On Tue, May 20, 2025 at 5:28 PM Roy Spencer <roywspencer@hotmail.com> wrote:  
This was after about 20 minutes of melting. <20250520\_192448.jpg>

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Roy Spencer <roywspencer@hotmail.com>  
Date: 5/20/25 7:15 PM (GMT-06:00)  
To: Steven Koonin <steven.koonin@gmail.com>, 'John Christy' <climateman60@gmail.com>, 'Ross McKittrick' <ross.mckittrick@gmail.com>  
Cc: 'Judith Curry' <curry.judith@gmail.com>, 'Travis Fisher' <travis.scott.fisher@gmail.com>  
Subject: RE: Tornado Emergency

I'll have time lapse video from our roofcam tomorrow. It was pretty impressive.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>

Date: 5/20/25 6:58 PM (GMT-06:00)

To: 'John Christy' <[climateman60@gmail.com](mailto:climateman60@gmail.com)>, 'Ross McKittrick' <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>

Cc: 'Judith Curry' <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>, "'Roy W. Spencer'" <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>, 'Travis Fisher' <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

Subject: RE: Tornado Emergency

Thoughts with you and yours. Stay safe!

---

**From:** John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>

**Sent:** Tuesday, May 20, 2025 7:54 PM

**To:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>

**Cc:** Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>; Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

**Subject:** Re: Tornado Emergency

Circulation passed right over our house, but funnel had lifted and we had only hail, horrible lightning, no dangerous wind.

Other storms still possible.

John C.

Sent from my iPhone

On May 20, 2025, at 6:28 PM, Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

Take care

On Tue, May 20, 2025 at 7:28 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

Large tornado headed our way. Potential catastrophic damage. Headed to safe room.

Again, great forecast Judy

John C.

Sent from my iPhone

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Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

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**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/21/2025 1:00:34 AM  
**To:** Roy Spencer [roywspencer@hotmail.com]  
**CC:** Steven Koonin [steven.koonin@gmail.com]; John Christy [climatemanager60@gmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
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Cc: 'Judith Curry' <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>, 'Travis Fisher' <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

Subject: RE: Tornado Emergency

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Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>

Date: 5/20/25 6:58 PM (GMT-06:00)

To: 'John Christy' <[climateman60@gmail.com](mailto:climateman60@gmail.com)>, 'Ross McKitrick' <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>

Cc: 'Judith Curry' <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>, "Roy W. Spencer" <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>, 'Travis Fisher' <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

Subject: RE: Tornado Emergency

Thoughts with you and yours. Stay safe!

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**From:** John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>

**Sent:** Tuesday, May 20, 2025 7:54 PM

**To:** Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>

**Cc:** Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>; Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

**Subject:** Re: Tornado Emergency

Circulation passed right over our house, but funnel had lifted and we had only hail, horrible lightning, no dangerous wind.

Other storms still possible.

John C.

Sent from my iPhone

On May 20, 2025, at 6:28 PM, Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:



Take care

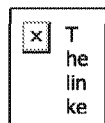
On Tue, May 20, 2025 at 7:28 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

Large tornado headed our way. Potential catastrophic damage. Headed to safe room.

Again, great forecast Judy

John C.

Sent from my iPhone



Judith Curry, President  
CFAN - Climate Forecast Applications  
Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) |  
+1.404.803.2012  
<http://www.cfanclimate.net>

---

**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 20, 2025 8:57 PM  
**To:** John Christy  
**Cc:** Ross McKittrick; Steve Koonin; Roy W. Spencer; Travis Fisher  
**Subject:** Re: Tornado Emergency

Yikes glad you are ok. Appreciate the confirmation of my forecast. I'll send you some screen shots of the forecast several days in advance when i have the chance. I had to do way too much multi-tasking, afraid my participation today was with half a brain.

On Tue, May 20, 2025 at 4:54 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

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CFAN - Climate Forecast Applications Network  
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[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

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**From:** Roy Spencer [roywspencer@hotmail.com]  
**Sent:** 5/21/2025 12:42:19 AM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]; Steven Koonin [steven.koonin@gmail.com]  
**CC:** John Christy [climateman60@gmail.com]; Judith Curry [curry.judith@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** RE: Tornado Emergency

Yup, that appears to be the only explanation.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Date:** 5/20/25 7:40 PM (GMT-06:00)  
**To:** Steven Koonin <steven.koonin@gmail.com>  
**Cc:** Roy Spencer <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Judith Curry <curry.judith@gmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Re: Tornado Emergency

The tornado gods heard you were going to write something about how they are becoming wimpier over time, and wanted to send a message.

On Tue, May 20, 2025 at 8:30 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

No doubt the WWA folks at Oxford would tell you it would only have been half an inch but for CO2

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**Cc:** 'Judith Curry' <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>; 'Travis Fisher' <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** RE: Tornado Emergency



This was after about 20 minutes of melting.

Sent from my Verizon, Samsung Galaxy smartphone

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Subject: RE: Tornado Emergency

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----- Original message -----

From: Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>

Date: 5/20/25 6:58 PM (GMT-06:00)

To: 'John Christy' <[climateman60@gmail.com](mailto:climateman60@gmail.com)>, 'Ross McKitrick' <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>

Cc: 'Judith Curry' <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>, "Roy W. Spencer" <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>, 'Travis Fisher' <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

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Thoughts with you and yours. Stay safe!

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Tuesday, May 20, 2025 8:40 PM  
**To:** Steven Koonin  
**Cc:** Roy Spencer; John Christy; Judith Curry; Travis Fisher  
**Subject:** Re: Tornado Emergency  
**Attachments:** image001.jpg

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**Subject:** RE: Tornado Emergency



This was after about 20 minutes of melting.

Sent from my Verizon, Samsung Galaxy smartphone

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----- Original message -----

From: Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>

Date: 5/20/25 6:58 PM (GMT-06:00)

To: 'John Christy' <[climateman60@gmail.com](mailto:climateman60@gmail.com)>, 'Ross McKittrick' <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>

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Sent from my iPhone

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Again, great forecast Judy

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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/21/2025 12:30:50 AM  
**To:** 'Roy Spencer' [roywspencer@hotmail.com]; 'John Christy' [climateman60@gmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]  
**CC:** 'Judith Curry' [curry.judith@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
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**To:** Steven Koonin; 'John Christy'; 'Ross McKittrick'  
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**To:** John Christy [climateman60@gmail.com]; Ross McKittrick [ross.mckitrick@gmail.com]  
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**Sent:** Tuesday, May 20, 2025 7:59 PM  
**To:** 'John Christy'; 'Ross McKitrick'  
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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
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**To:** John Christy  
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John C.  
Sent from my iPhone

---

**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Thursday, May 15, 2025 8:40 PM  
**To:** Steven Koonin  
**Cc:** John Christy; Roy W. Spencer; Ross McKittrick; Travis Fisher  
**Subject:** Re: now available Monday and Tuesday (and a question)

I was thinking the lead author would edit the chapter on the screen in real time as we go through it on the call

On Thu, May 15, 2025 at 3:38 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

I've cancelled my trip to DC next week so will be available to zoom on Monday/Tuesday as we go through chapter by chapter.

Now the question(s):

- How are we handling edits/corrections/comments to the individual chapters in the DropBox folder 01.Report? Circulating our individual docs by email will surely produce version control issues.
- Suggest Ross creates a "Comments" folder where we can each upload our comments for each chapter. If we keep the same naming convention they'll be pretty easy to compile.
- And I (at least) can't figure out how to upload to the DropBox folder 01.Report. If a "Comments" folder is created, we all need upload privs to that.

Steve Koonin

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Thursday, May 15, 2025 6:39 PM  
**To:** 'Judith Curry'; 'John Christy'; 'Roy W. Spencer'; 'Ross McKittrick'; 'Travis Fisher'  
**Subject:** now available Monday and Tuesday (and a question)

I've cancelled my trip to DC next week so will be available to zoom on Monday/Tuesday as we go through chapter by chapter.

Now the question(s):

- How are we handling edits/corrections/comments to the individual chapters in the DropBox folder 01.Report? Circulating our individual docs by email will surely produce version control issues.
- Suggest Ross creates a "Comments" folder where we can each upload our comments for each chapter. If we keep the same naming convention they'll be pretty easy to compile.
- And I (at least) can't figure out how to upload to the DropBox folder 0.1Report. If a "Comments" folder is created, we all need upload privs to that.

Steve Koonin

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**From:** Ross McKitrick <ross.mckitrick@gmail.com>  
**Sent:** Tuesday, May 20, 2025 9:04 AM  
**To:** Steven Koonin  
**Cc:** Roy W. Spencer; Judith Curry; John Christy; Travis Fisher  
**Subject:** Re: post-meeting drafts

I'm doing some work on Ch 3 to add in material sent to me via email so don't anyone else work on the post-meeting version. Thx

On Tue, May 20, 2025 at 8:31 AM Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:

Try this

<https://www.dropbox.com/scl/fo/3himuruwfurnz90w9owex/AOxdIWpSyg7A7KBWz2GtwcA?rlkey=5t1vdx21yef103sj06jh2ect8&dl=0>

On Tue, May 20, 2025 at 8:07 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Ross – Can't see this new folder you send me a link

Thanks, SEK

---

**From:** Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>  
**Sent:** Monday, May 19, 2025 6:36 PM  
**To:** Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>  
**Subject:** post-meeting drafts

I have opened a new folder called Post-meeting versions which will hold the drafts as they stand after we have gone through them.

You should all have access to them but if not let me know.

With regards to the remaining minor changes in Ch 5 in order to control the process when you change a draft if it's just a revised figure and caption, or a new paragraph, you can send it to me via email and I'll insert it, but if you change the draft in the Dropbox folder add [AB] initials to the file name so we keep track of the version change.

I didn't upload extreme weather yet since we have work to do on it tomorrow.



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**From:** Ross McKitrick <ross.mckitrick@gmail.com>  
**Sent:** Tuesday, May 20, 2025 8:32 AM  
**To:** Steven Koonin  
**Cc:** Roy W. Spencer; Judith Curry; John Christy; Travis Fisher  
**Subject:** Re: post-meeting drafts

Try this

<https://www.dropbox.com/scl/fo/3himuruwfurnz90w9owex/AOxdIWpSyg7A7KBWz2GtwcA?rlkey=5t1vdx21yef103sj06jh2ect8&dl=0>

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 20, 2025 8:08 AM  
**To:** 'Ross McKitrick'; 'Roy W. Spencer'; 'Judith Curry'; 'John Christy'; 'Travis Fisher'  
**Subject:** RE: post-meeting drafts

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**To:** Roy W. Spencer <roywspencer@hotmail.com>; Judith Curry <curry.judith@gmail.com>; John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@gmail.com>  
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I didn't upload extreme weather yet since we have work to do on it tomorrow.



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**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Saturday, May 17, 2025 12:27 PM  
**To:** Ross McKitrick  
**Subject:** Re: read this version - tipping points

MUCH better

On Sat, May 17, 2025 at 9:23 AM Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:

I tried not to turn it into a math lecture but there's a real terminology gap between the literature and the IPCC/Lenton stuff and the difference is important. I find the IPCC terminology pretty baffling so I steer away from terms like noise bifurcation. In the end I think we make a decent case that the tipping point concept doesn't have much bearing on SCC calculations.

On Sat, May 17, 2025 at 8:59 AM Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)> wrote:

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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/17/2025 4:23:06 PM  
**To:** Judith Curry [curry.judith@cfanclimate.com]  
**Subject:** Re: read this version - tipping points  
**Attachments:** tipping points.May17[RM].docx

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On Sat, May 17, 2025 at 8:59 AM Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)> wrote:

#### 12.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon (SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz et al. 2021). They are often referred to as “tipping points.”

The term “tipping point” mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly’s wings (Shen et al. 2014). The term “tipping point” is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily depend on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth’s climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the latter is a possibility. Kypke et al. (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon 2023).

The possible existence of bifurcations in the Earth’s climate system implies abrupt transitions are possible, not just in response to large forcing but to small perturbations as well. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos et al 2024) and indeed may not be able to since one implication of the “butterfly effect” is the existence of predictability boundaries of nonlinear systems (Palmer et a. 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict or prevent it from happening.

The IPCC AR6 (Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the “tipping point”

concept in discussions of climate change (see <https://report-2023.global-tipping-points.org/what-is-a-tipping-point/> for example). As summarized by the IPCC AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO<sub>2</sub> concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by The Global Tipping Points Report that was launched at the COP28 on 6 December 2023 (Lenton et al., 2023) <https://report-2023.global-tipping-points.org>. It identifies more than 25 parts of the climate system said to constitute tipping points. What gets classified as a climate “tipping point” is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of the Greenland and West Antarctic ice sheets. These impacts can be reversed on the decadal timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). The IPCC AR6 WG1 Summary for Policy Makers states:

"The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is high confidence in the 21st century decline, there is only low confidence in the magnitude of the trend. There is medium confidence that there will not be an abrupt collapse before 2100." (C.3.4)

"There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5)." (B.5.2)

For the purpose of SCC calculations the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. The IPCC AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz et al. incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there may be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been taken into account the result is only

a modest increase in the SCC value in the 21<sup>st</sup> century.

Dietz, S., J. Rising, T. Stoerk, G. Wagner (2021) Economic impact of tipping points in the climate system. *PNAS* 2021 Vol. 118 No. 34 e2103081118

Shen, Bo-Wen, Roger A Pielke Sr and Xubin Zeng (2023) The 50th Anniversary of the Metaphorical Butterfly Effect since Lorenz (1972): Multistability, Multiscale Predictability, and Sensitivity in Numerical Models. *Atmosphere* 2023 14(8) <https://doi.org/10.3390/atmos14081279>

Crawford, John D (1991) Introduction to Bifurcation Theory. *Reviews of Modern Physics* 63(4) October 1991 991—1037.

Kypke, K. L., Langford, W. F., and Willms, A. R.: Anthropocene climate bifurcation, *Nonlin. Processes Geophys.*, 27, 391–409, <https://doi.org/10.5194/npg-27-391-2020>, 2020.

Brunetti, Maura and Charline Ragon (2023) Attractors and bifurcation diagrams in complex climate models. *Physical Review E* 107 054214  
<https://journals.aps.org/pre/abstract/10.1103/PhysRevE.107.054214>

Dakos, Vasilis, Chris Boulton, Joshua Buxton et al. (2024) Tipping point detection and early warnings in climate, ecological, and human systems. *Earth System Dynamics* 15 1117—1135  
<https://doi.org/10.5194/esd-15-1117-2024>

Palmer, TN, A Döring and G Seregin (2014) The real butterfly effect. *Nonlinearity* 27(9) 10.1088/0951-7715/27/9/R123 <https://iopscience.iop.org/article/10.1088/0951-7715/27/9/R123/meta>

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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Friday, May 16, 2025 6:02 PM  
**To:** Judith Curry; Travis Fisher  
**Cc:** Ross McKittrick; Steven Koonin; John Christy  
**Subject:** RE: Report formatting/structure

Good point.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Judith Curry <curry.judith@cfanclimate.com>  
Date: 5/16/25 2:55 PM (GMT-06:00)  
To: Travis Fisher <travis.scott.fisher@gmail.com>  
Cc: Ross McKittrick <ross.mckittrick@gmail.com>, Steven Koonin <steven.koonin@gmail.com>, John Christy <climatemanager60@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>  
Subject: Re: Report formatting/structure

I have also been thinking that the tail pipe emissions chapter doesn't make a lot of sense for the way we are motivating and laying out this report; this chapter makes the report look like a direct request from the EPA since we focus directly on this topic. I agree with adding Ch 13 to Ch 12 as an "example"

On Fri, May 16, 2025 at 12:08 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:  
Hi all,

I've gone through and made a first round of changes to the chapter and section numbering. I say first round because I'm sure I missed things (especially the references within the body that cite figures and tables in other sections, etc.), and I'll keep checking. Once we combine the chapters into a single document, we might want to create a live/linkable table of contents with section headings that renumber automatically.

We should also figure out a consistent style for fonts, colors, etc.--obviously not a top priority right now, but here's the example I would offer regarding style (this is the DOE report I led in 2017): [https://www.energy.gov/sites/prod/files/2017/08/f36/Staff%20Report%20on%20Electricity%20Markets%20and%20Reliability\\_0.pdf](https://www.energy.gov/sites/prod/files/2017/08/f36/Staff%20Report%20on%20Electricity%20Markets%20and%20Reliability_0.pdf) Something to think about.

The following two sentences from the end of Chapter 3 could work well in Chapter 13: "The practice of referring to unilateral US reductions as 'combatting climate change' or 'taking action on climate' reflects a profound misunderstanding of the scale of the issue. The scale problem is compounded by recognizing that U.S. motor vehicles account only for about 4 percent of global CO2 emissions so that even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate."

Given that Chapter 13 is very thin, we could also combine Chapters 12 and 13 and rename it something like "Climate Change and the US Economy."

Any thoughts/reactions?

Best,  
Travis

---

**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Friday, May 16, 2025 4:52 PM  
**To:** Travis Fisher  
**Cc:** Steven Koonin; Judith Curry; John Christy; Roy W. Spencer  
**Subject:** Re: Report formatting/structure

I don't know the people well enough to ensure against leaks so I guess we'll go with the DoE department. I have document templates that make it easy to convert to formatted headings with automatic numbering and table of content codes. When we get to that stage I can help with those steps.

On Fri, May 16, 2025 at 4:41 PM Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:

I'm most comfortable handling the final production within the DOE's Department of Fancy Documents (me, Josh, and the data viz whiz), in part because I'm worried about leaks from anyone outside of this group at the late stages. Ross, are you talking about University folks or people on your contractor's team? If you know and trust them, I'm open to getting some help in the final push.

Totally agree on Chapter 13, especially if we're going to publish before and independent of the EPA's rulemaking. I also think we can broaden that part to all US CO2 emissions and just touch on the top anthropogenic sources (vehicles in their various categories, power plants, industry, etc). I imagine we can pull in a pie chart from EPA or EIA.

On Fri, May 16, 2025 at 4:30 PM Ross McKittrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:

Regarding the font and live headings issue, when I've written for think tanks who have their own document production teams they request a final draft with no formatting because it makes easier that way for them to insert the formatting. So how we proceed on that issue will depend on what the Department is able to offer for document production. If we're on our own then I could ask people I work with here if they could take on a rush job.

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The following two sentences from the end of Chapter 3 could work well in Chapter 13: "The practice of referring to unilateral US reductions as 'combatting climate change' or 'taking action on climate' reflects a profound misunderstanding of the scale of the issue. The scale problem is compounded by recognizing that U.S. motor vehicles account only for about 4 percent of global CO2 emissions so that even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate."

Given that Chapter 13 is very thin, we could also combine Chapters 12 and 13 and rename it something like "Climate Change and the US Economy."

Any thoughts/reactions?

Best,  
Travis

---

**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Friday, May 16, 2025 3:55 PM  
**To:** Travis Fisher  
**Cc:** Ross McKittrick; Steven Koonin; John Christy; Roy W. Spencer  
**Subject:** Re: Report formatting/structure

I have also been thinking that the tail pipe emissions chapter doesn't make alot of sense for the way we are motivating and laying out this report; this chapter makes the report look like a direct request from the EPA since we focus directly on this topic. I agree with adding Ch 13 to Ch 12 as an "example"

On Fri, May 16, 2025 at 12:08 PM Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:  
Hi all,

I've gone through and made a first round of changes to the chapter and section numbering. I say first round because I'm sure I missed things (especially the references within the body that cite figures and tables in other sections, etc.), and I'll keep checking. Once we combine the chapters into a single document, we might want to create a live/linkable table of contents with section headings that renumber automatically.

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Travis

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**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Friday, May 16, 2025 3:08 PM  
**To:** Ross McKittrick  
**Cc:** Steven Koonin; Judith Curry; John Christy; Roy W. Spencer  
**Subject:** Report formatting/structure

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Any thoughts/reactions?

Best,  
Travis

---

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Saturday, May 17, 2025 2:09 PM  
**To:** Judith Curry  
**Cc:** Steven Koonin; Travis Fisher; Roy W. Spencer; John Christy  
**Subject:** Re: Ch 3  
**Attachments:** image001.png; 2 Direct impacts.May17.docx

I inserted them with supporting text in the attached version.

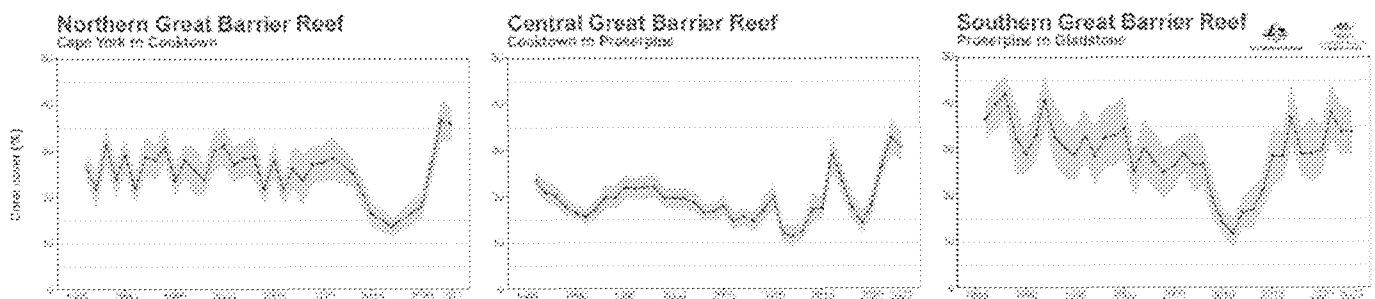
On Sat, May 17, 2025 at 1:50 PM Judith Curry <curry.judith@gmail.com> wrote:  
Definitely good to include these graphics

On Sat, May 17, 2025 at 10:11 AM Steven Koonin <steven.koonin@gmail.com> wrote:

You can find an “official” figure on the rebound of the GBR in the AIMS report,  
[https://www.aims.gov.au/sites/default/files/2023-08/QuickLook\\_AIMS\\_LTMP\\_Report\\_GBR\\_coral\\_status\\_22\\_23.pdf](https://www.aims.gov.au/sites/default/files/2023-08/QuickLook_AIMS_LTMP_Report_GBR_coral_status_22_23.pdf)

I’ve pasted it below. We should include it in the text, I think.

Amusingly, the report says “The results indicate the recent widespread recovery in the Northern and Central regions of the Great Barrier Reef has paused.” It could have just as well said “Coral levels across the reef are now at least as high as they were forty years ago.”



*Regional trends in the percentage of hard coral cover on the Northern, Central and Southern Great Barrier Reef from manta tow surveys by the AIMS Long-Term Monitoring Program up to the 2022/23 survey year.*

---

**From:** Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Sent:** Friday, May 16, 2025 11:35 AM  
**To:** Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>  
**Cc:** Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Subject:** Ch 3

I didn't see Chapter 3 in the new "01.Report Draft" folder, so I just added the version that includes my comment bubbles to the folder. I'm also attaching it here for convenience.

Excellent work.

For the rest of the chapters, I'll plan to add comment bubbles directly to the version in the "01.Report Draft" folder.

On Thu, May 15, 2025 at 6:54 PM Ross McKitrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:

Steve you should write a Figure caption for the chapter explaining that.

On Thu, May 15, 2025 at 6:33 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

On Figure 2.2:

I constructed that figure from Figure 3 on pg 192 of this paper: <https://ajsonline.org/article/61570-geocarb-iii-a-revised-model-of-atmospheric-co-2-over-phanerozoic-time>

As you can see from the penultimate paragraph on pg 191 of that paper, “a rough value of 300 ppm” is used to represent the present. So “today” would plot as 1.3 on the graph. In fact, here is the caption from the figure as it appears in “Unsettled”

**Figure 3.3 Atmospheric concentration of carbon dioxide**

**beginning at 550 million years ago. Values determined from the**



isotopic ratio in carbonate sediments and fossilized soils are relative to the average over the past few million years; today's concentration would be about 1.3 on this scale, down in the lower right-hand corner.<sup>5</sup>

Hope this helps.

SEK

---

**From:** Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Sent:** Thursday, May 15, 2025 5:18 PM  
**To:** Ross McKittrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)>  
**Cc:** Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Subject:** Ch 2

Hi all,

I had a few questions about Chapter 2 (in bubbles in the attached document). My goal is to read closely and comment on every chapter before you guys have your marathon walk-through call. Excellent job on this--I didn't realize how strong the effect of CO<sub>2</sub> was on crop water productivity.

Best,

Travis



Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

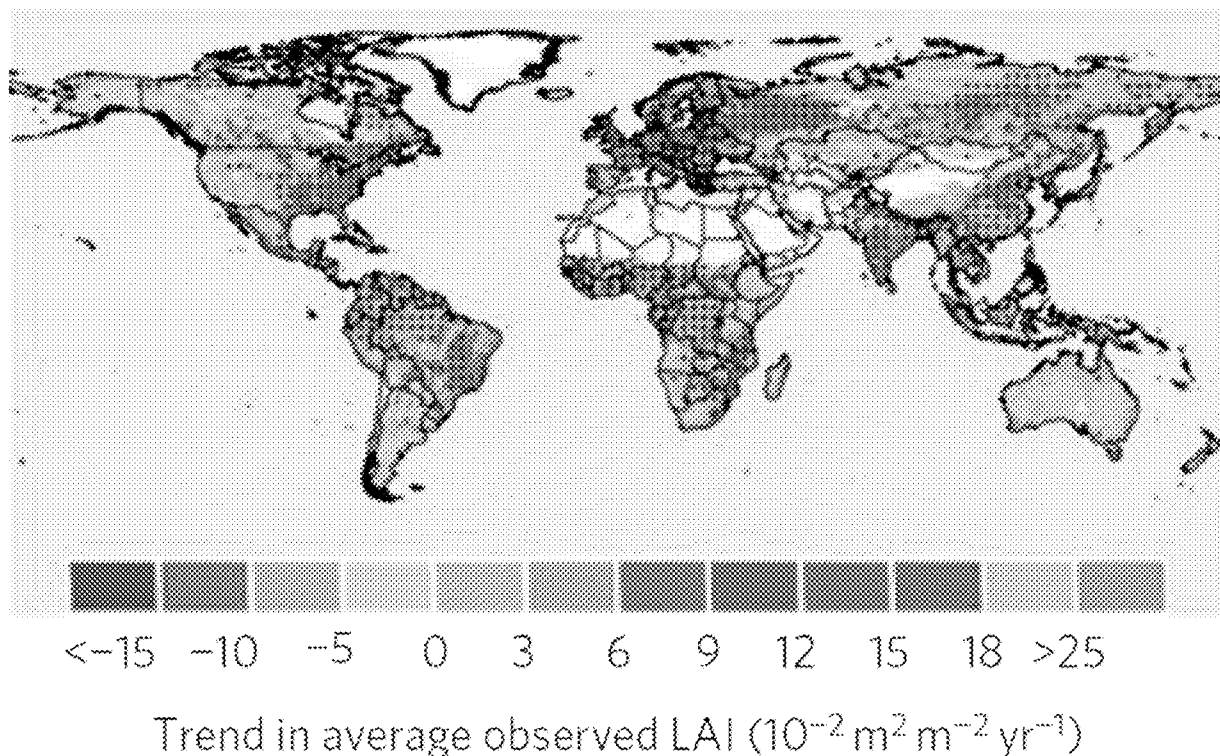
## 2 Direct Impacts of CO<sub>2</sub> on the environment

### 2.1 CO<sub>2</sub> and global greening

The growing CO<sub>2</sub> concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the “global greening” phenomenon discussed below, as well as in the improving agricultural yields discussed in Chapter 10.

#### 2.1.1 Measurement of global greening

“Greening” refers to an increase in the fraction of the Earth’s surface covered by plants. It can be quantified by the “Leaf Area Index” (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO<sub>2</sub> levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50% of the Earth versus “browning” over only 4%, and attributed 70% of the greening to rising CO<sub>2</sub> levels (see Figure 2.1).



**Figure 2.1:** Trends in average Leaf Area Index (LAI). Source: Zhu et al. 2016 Figure 3.

Zheng (2017) confirmed the pattern, noting that greening over thirty years had added 8% to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen et al. (2019) noted that China and India were exploiting it though land management changes. Thus while China accounts for only 6.6% of global vegetated area it accounts for 25% of global net increase in LAI. Piao et al. (2020) noted that greening was even observable in the Arctic.

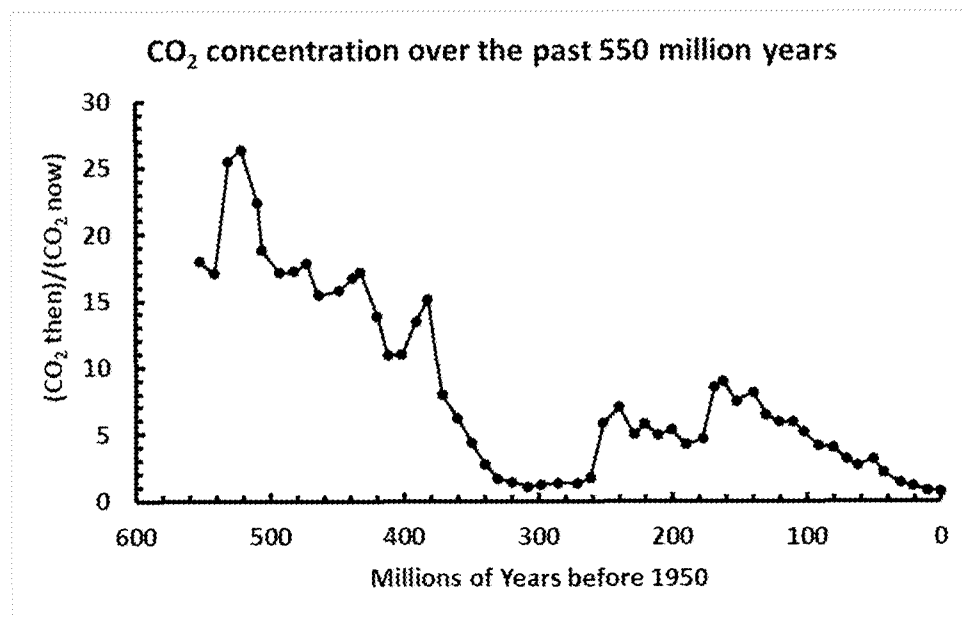
While plant models predict increases in photosynthesis in response to rising CO<sub>2</sub>, Haverd et al. (2020) reported a CO<sub>2</sub> fertilization rate nearly double what models had predicted. That is, CO<sub>2</sub> fertilization had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO<sub>2</sub> have likely understated the benefits to crops and agriculture. The connection between CO<sub>2</sub> fertilization and climate policy will be discussed in Chapter 10.

Finally, Chen et al. surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55% of the globe while browning was accelerating over only 7%. In other words, the greening trend continued with no evidence of slowdown, and CO<sub>2</sub> fertilization remained the dominant driver

### 2.1.2 Photosynthesis and CO<sub>2</sub> levels

Plants build biomass through *photosynthesis*, a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is called Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO<sub>2</sub> is available at the surface of the RuBisCo enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the “C3” process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO<sub>2</sub> levels were usually many times higher than they are today, as shown in Figure 2.2



**Figure 2.2.** Ambient CO<sub>2</sub> levels over the past 550 million years as a multiple of current levels. Source: Adapted from Berner (2006). Current CO<sub>2</sub> levels correspond to about 1.3 times the indicated value at 0.

About 400 million years ago CO<sub>2</sub> levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd et al. 2024).

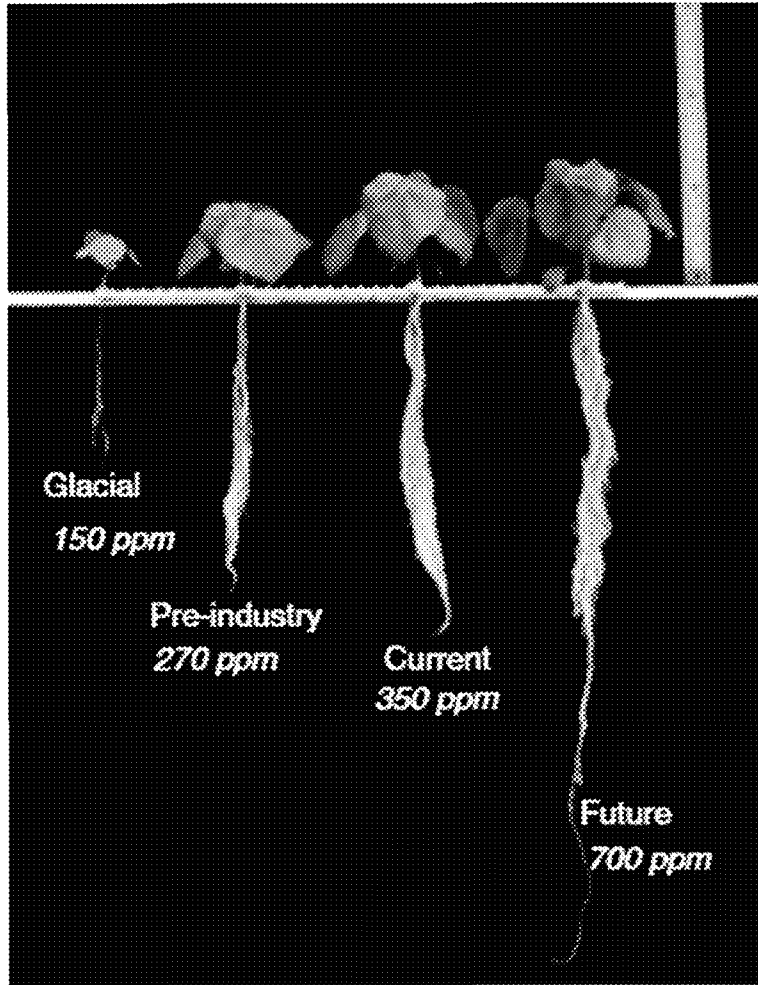
Over the past 35 million years the level of atmospheric CO<sub>2</sub> has been steadily declining. During glaciations levels have fallen as low as 170 ppm (Gerhart and Ward 2010).

In response to low-CO<sub>2</sub> conditions some plants evolved another photosynthetic pathway called C4, in which CO<sub>2</sub> is concentrated in the vicinity of Rubisco allowing for the C3 process to function more efficiently. For agricultural purposes the plant categories are:

- C3: rice, wheat, soybeans and most other crops
- C4: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO<sub>2</sub> levels continued declining, plant growth rates would have declined and eventually ceased. Below 180 ppm many C3 species experience growth rate reductions on the order of 40-60% compared to their growth rates at 350 ppm (Gerhart and Ward 2010). C3 plants have been observed under experimental conditions to stop growing altogether at levels between 60—140 ppm CO<sub>2</sub>. Some C4 plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Currently, CO<sub>2</sub> levels are about 420 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO<sub>2</sub> is illustrated in Figure 2.3 which is reproduced from Gerhart and Ward (2010). It shows the growth effect of CO<sub>2</sub> on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO<sub>2</sub> exposure is varied. The gains exhibited from increasing CO<sub>2</sub> from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.



**Figure 2.3:** growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO<sub>2</sub> levels. Source: Gerhart and Ward (2010).

Over the past 60+ years there have been thousands of studies on the response of plants to rising CO<sub>2</sub> levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO<sub>2</sub>. There are two mechanisms by which CO<sub>2</sub> confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO<sub>2</sub> by opening the stomata (pores) on the leaf surface. When CO<sub>2</sub> is scarce the stomata must be kept wide open for long periods, which allows water to evaporate away. Under enriched CO<sub>2</sub> conditions the stomata are closed for longer periods helping the plant retain water longer, thereby increasing water use efficiency.

Specific effects of climate change on US agriculture will be reviewed in Chapter 10.

### 2.1.3 Rising CO<sub>2</sub> and crop water use efficiency

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO<sub>2</sub> Enrichment—see Chapter 10) on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them so that all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

Similarly, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

#### *2.1.4 Concealment of CO<sub>2</sub> fertilization benefits in IPCC Reports*

If CO<sub>2</sub> emissions had been discovered to be causing global crop declines and regional browning, that surely would have been discussed prominently in IPCC reports, perhaps even with its own chapter in an Assessment Report if not an IPCC Special Report. By contrast the IPCC has been almost silent on the topic of global greening and CO<sub>2</sub> fertilization of agricultural crops.

The topic is briefly acknowledged in a few places in the body of the IPCC 6<sup>th</sup> and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report entitled “global greening and browning” points out that the IPCC Special Report on Climate Change and Land had concluded with *high confidence* that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO<sub>2</sub> fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

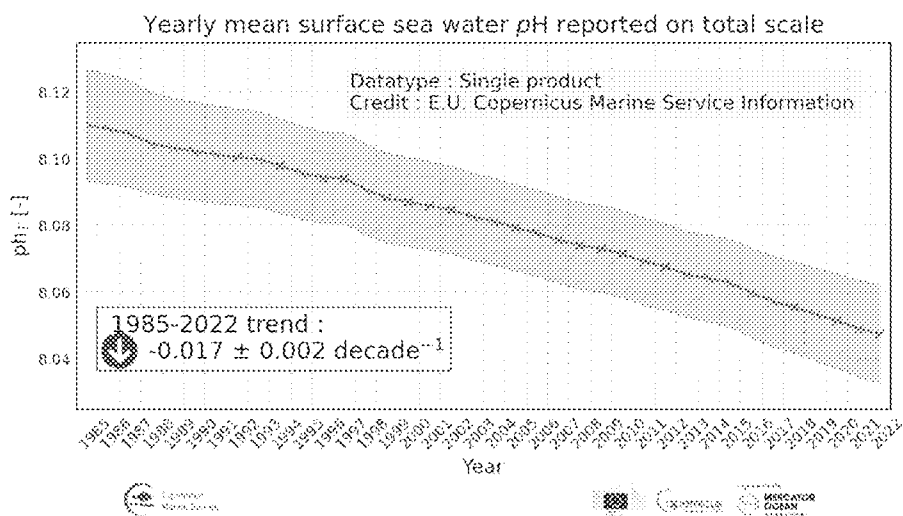
Overall, however, the Policymaker Summaries, Technical Summaries and Synthesis Reports conspicuously fail to discuss the topic.

## **2.2 Ocean Alkalinity**

### *2.2.1 Changing pH*

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is basic and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO<sub>2</sub> concentrations in the atmosphere increase, more is absorbed

by the oceans, which decreases alkalinity. Depending upon the buffering capacity of the oceans, the oceans are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.



**Figure 2.4:** Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

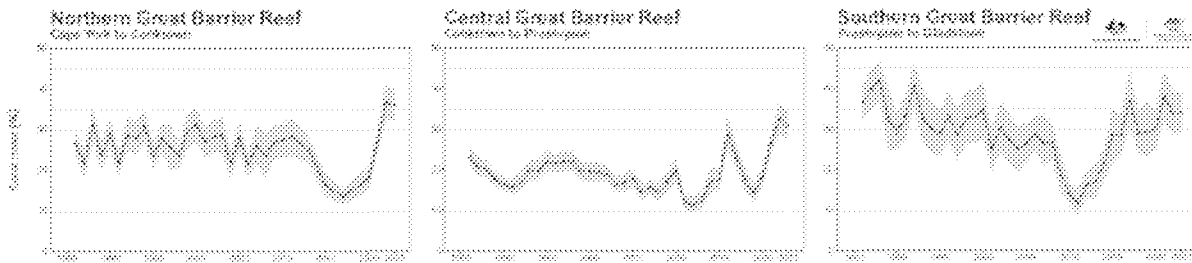
While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 - to 7.0 (Krissansen-Totton et al., 2018). On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

### 2.2.2 Coral reef changes

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De’ath et al. (2009) reported that a portion of Australia’s Great Barrier Reef (GBR, the world’s largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd et al. (2013) showed that report to have resulted from a biased data analysis which, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study compared to only 11 citations for the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates a strong rebound has occurred in coral production (AIMS, 2023). Figure 2.5 shows the results of the AIMS surveys of hard coral cover, expressed as a percentage of the reef area. Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods

Hole 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO<sub>2</sub> levels the rebound has come as a surprise to some observers.



**Figure 2.5** Hard coral cover of three regions of the Great Barrier Reef 1985 to 2023. Source: AIMS 2023.

### 2.2.3 Publication bias

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the impacts of declining ocean pH. An *ICES Journal of Marine Science* Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, “As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish.” (Browman, 2016)

Similarly, a meta-analysis (Clements et al., 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a “decline effect”: initially dramatic conclusions published in prominent journals showing apparently large reported effects of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to prevent the “decline effect” from persisting:

[The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research.

Clements et al. (2022)

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. Changes to the Australian Great Barrier Reef are driven by many factors other than temperatures or alkalinity and coral cover has recently staged a major rebound. Much of the public discussion of the effects of ocean “acidification” on marine biota has been one-sided and exaggerated. There is a known tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, then subsequent research rebutting those findings receives little attention.



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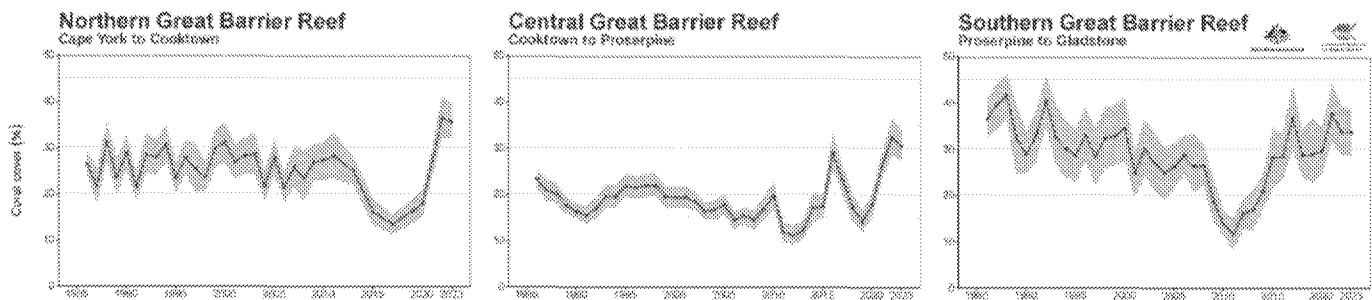
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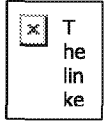
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CFAN - Climate Forecast Applications  
Network  
Reno, NV USA  
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+1.404.803.2012  
<http://www.cfanclimate.net>

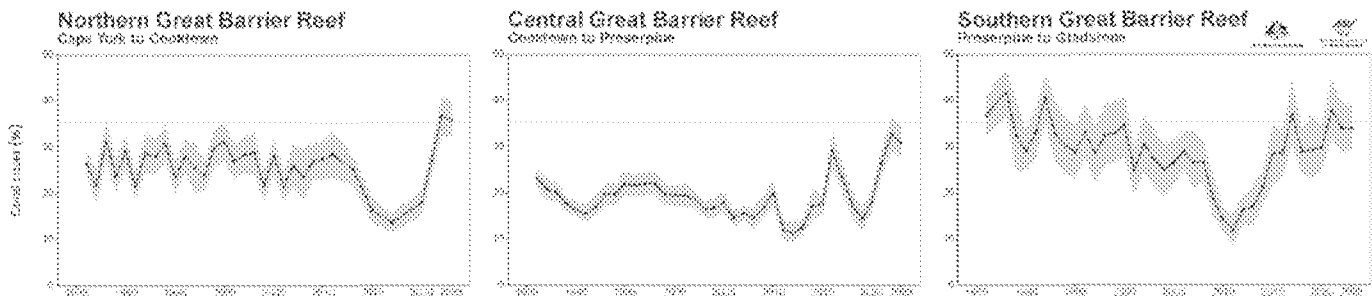
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**Attachments:** image001.png

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**To:** Ross McKitrick  
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**Subject:** Re: Ch 3

I migrated my comments on the ocean section to the material in the dropbox (now the second half of chapter 2). Sorry for missing the merger conversation!

Now I'm going through and changing the rest of the numbering. I won't track these numbering changes because it would be a mess.

On Fri, May 16, 2025 at 11:40 AM Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:

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**Subject:** Ch 2

Hi all,

I had a few questions about Chapter 2 (in bubbles in the attached document). My goal is to read closely and comment on every chapter before you guys have your marathon walk-through call. Excellent job on this--I didn't realize how strong the effect of CO2 was on crop water productivity.

Best,

Travis



### 3. Increasing CO<sub>2</sub> and the Alkaline Oceans

*{Ross May 12 edit notes: added citation for pH figure. Moved paleo paragraph closer to start. It was decided to reword various paragraphs to remove passive tense where possible. Expanded discussion of Clements et al – quite an important article – and updated the citation to the published version. Expanded the concluding paragraph}*

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is basic and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO<sub>2</sub> concentrations in the atmosphere increase, more is absorbed by the oceans, which decreases alkalinity. Depending upon the buffering capacity of the oceans, the oceans are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.

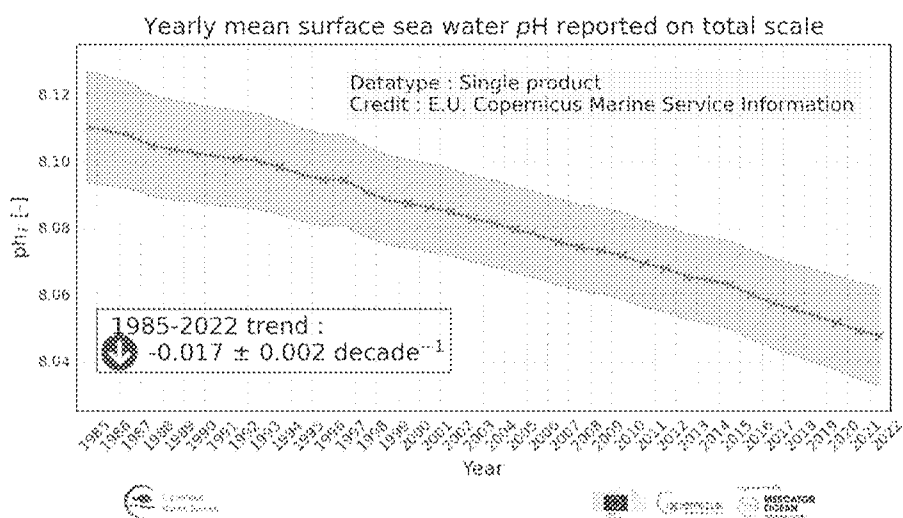


Figure 3.1: Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 - to 7.0 (Krissansen-Totton et al., 2018). On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De’ath

et al. (2009) reported that a portion of Australia's Great Barrier Reef (GBR, the world's largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd et al. (2013) showed that report to have resulted from a biased data analysis which, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study compared to only 11 citations for the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates a strong rebound has occurred in coral production (AIMS, 2022). Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods Hole 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO<sub>2</sub> levels the rebound has come as a surprise to some observers.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the impacts of declining ocean pH. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, "As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish." (Browman, 2016)

Similarly, a meta-analysis (Clements et al., 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a "decline effect": initially dramatic conclusions published in prominent journals showing apparently large reported effects of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to prevent the "decline effect" from persisting:

[The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research.

Clements et al. (2022)

In conclusion, much of the public discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated. Ocean life is complex and much of it evolved when the oceans were acidic relative to the present. There is a tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, whereas the subsequent research rebutting those findings tends to receive little attention.

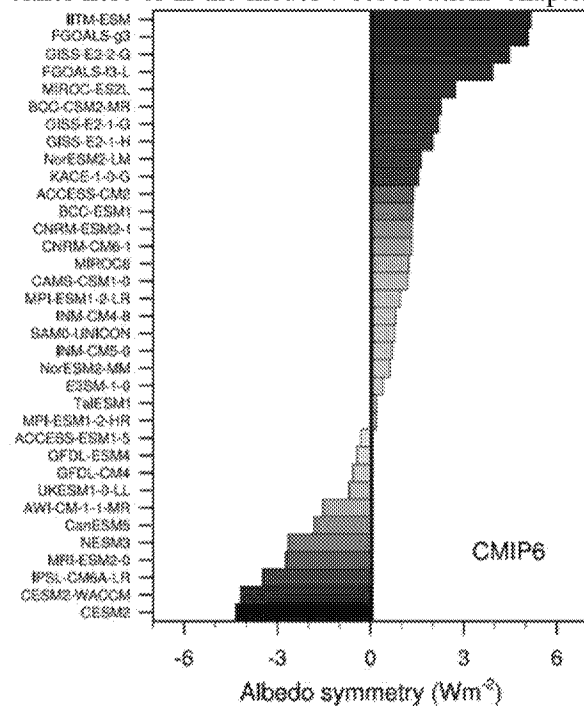
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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/18/2025 6:02:56 PM  
**To:** 'Roy Spencer' [roywspencer@hotmail.com]; 'Judith Curry' [curry.judith@cfanclimate.com]; 'John Christy' [climateman60@gmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** RE: new text: declining planetary albedo  
**Attachments:** image002.jpg

I'll read through this section when I finish up the others. Meanwhile, two points:

1. We were pleased to have seen the albedo decline in earthshine observations during 2015-2017 (published GRL 2021 <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GL094888> ) Note I don't advocate including this as a reference
2. As a further indication that the models are, to put it politely, "deficient", there is this graph that we might include either here or in the model v observations chapter:



**Caption:** Differences in the reflectivity (albedo) between the Northern and Southern Hemispheres for members of the model ensemble used in the most recent IPCC assessment. The very small observed difference is indicated by the vertical black line.

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Sunday, May 18, 2025 12:31 PM  
**To:** Judith Curry <curry.judith@cfanclimate.com>; John Christy <climateman60@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Re: new text: declining planetary albedo

I made several edits... One being the reason why decreasing albedo is even being mentioned: record global-average warmth.

---

**From:** Judith Curry <[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com)>

**Sent:** Sunday, May 18, 2025 10:42 AM

**To:** John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

**Subject:** new text: declining planetary albedo

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---

**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Sunday, May 18, 2025 12:53 PM  
**To:** Roy Spencer  
**Cc:** Judith Curry; John Christy; Steven Koonin; Travis Fisher  
**Subject:** Re: new text: declining planetary albedo  
**Attachments:** Declining planetary albedo.May18.[JC][RS]RM].docx

This looks excellent Judy.

I added a couple of sentences to the first paragraph for the benefit of non-experts. Agree with Roy that the connection to recent warmth is important.

On Sun, May 18, 2025 at 12:30 PM Roy Spencer <roywspencer@hotmail.com> wrote:

I made several edits... One being the reason why decreasing albedo is even being mentioned: record global-average warmth.

---

**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Sunday, May 18, 2025 10:42 AM  
**To:** John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckitrick@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
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## Declining planetary albedo and recent record warmth

Planetary albedo is the fraction of incoming solar radiation that is reflected back into space by reflective surfaces like cloud tops and snow, rather than being absorbed at the surface. Earth's planetary albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed at the surface to be then re-radiated as heat into the atmosphere. Hence, other things being equal, a decline in Earth's albedo is associated with a warming of the atmosphere.

Arguably the most striking change to the Earth's climate system in the 21<sup>st</sup> century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure xxx shows the planetary albedo variations since 2000, when we have good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m<sup>2</sup> in solar energy averaged over the planet (Hansen and Karecha, 2025). For reference, doubling of CO<sub>2</sub> has a direct radiative impact of about 1.2 W/m<sup>2</sup>.

Looking back prior to 2000 with less adequate data, Gossling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before industrial aerosol precursor emissions led to global dimming until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.

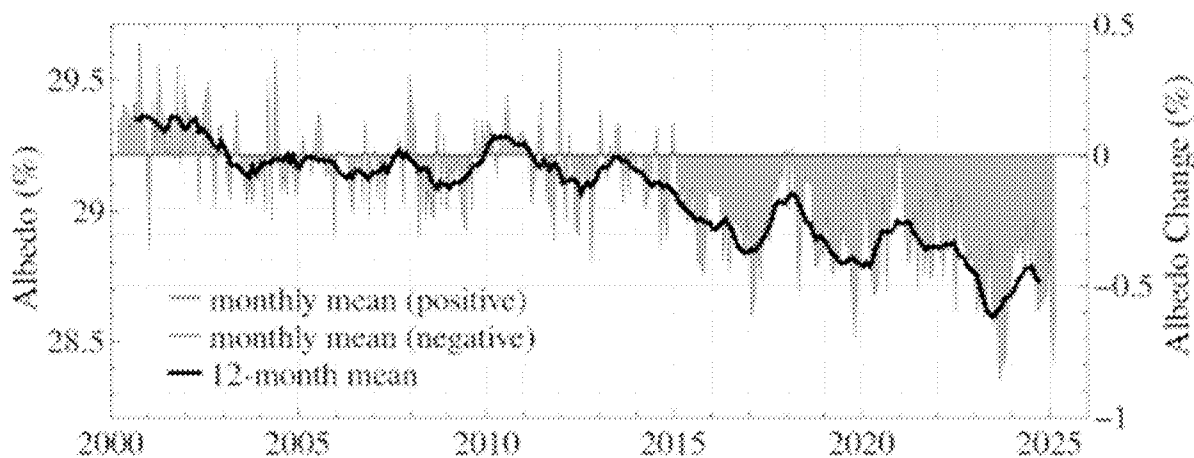


Figure xxx. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface characteristics can't explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5% since 1980 ([https://nsidc.org/data/seaice\\_index/images/s\\_plot\\_hires.png](https://nsidc.org/data/seaice_index/images/s_plot_hires.png)), although following 2007 there has been a pause in the Arctic sea ice decline (England et al., 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (SPM, A.1.5)
- Northern hemispheric snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer.  
<http://climate.rutgers.edu/snowcover/>

- Global greening (Chapter 2) is contributing the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

This leaves the most likely explanation for the sharp albedo decline as being caused by changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. In terms of pollution aerosol, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog et al., 2024; Yuan et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb et al., 2024; Gosling et al 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the northern hemisphere, whereas in the southern hemisphere the decrease in planetary albedo is primarily from decreases in mid-level clouds across all latitude zones. Gossling et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was the strongest El Nino event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).
- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019



- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Nino Southern Oscillation (ENSO), which have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gossling et al. (2025) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz et al, 2025; Kuchar et al., 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO<sub>2</sub>. While it is difficult to untangle causes of the trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming, or a temporary fluctuation driven by natural variability

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G. Schmidt, Climate models can't explain 2023's huge heat anomaly — we could be in uncharted territory. *Nature* 627, 467 (2024).

Ø. Hodnebrog et al., Recent reductions in aerosol emissions have increased Earth's energy imbalance. *Commun Earth Environ* 5, 166 (2024). doi:10.1038/s43247-024-01324-8

13. T. Yuan, et al., Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming. *Commun Earth Environ* 5, 281 (2024). doi:10.1038/s43247-024-01442-3

Mark England, Lorenzo M Polvani, James A Screen, et al. Surprising, but not unexpected, multi-decadal pause in Arctic sea ice loss. *ESS Open Archive* . March 29, 2025.

Hansen J and P Karecha (2025) Large cloud feedback confirms high sensitivity  
<https://mailchi.mp/caa/large-cloud-feedback-confirms-high-climate-sensitivity>

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Loeb, N., S-H Ham, RP Allen, TJ Thorsen, B Meyssignac, S Kato, GC Johnson, JL Lyman,(2024) Observational Assessment of Changes in Earth's Energy Budget since 2000. *Surveys in Geophysics*, 45, 1757-1783

Desbruyeres, D, L Chafik and G Maze (2021) A shift in the ocean circulation has warmed the subpolar North Atlantic Ocean since 2016. *Communications Earth&Environment*.

Arthun, M, RCJ Willis, HL Johnson, L Chafik, HR Langehaug (2021) Mechanisms of Decadal North Atlantic Climate Variability and Implications for the Recent Cold Anomaly. *Journal of Climate*, Vol 34

Kuchar, A., Sukhodolov, T., Chiodo, G., Jörimann, A., Kult-Herdin, J., Rozanov, E., and Rieder, H. H.: Modulation of the northern polar vortex by the Hunga Tonga–Hunga Ha'apai eruption and the associated surface response, *Atmos. Chem. Phys.*, 25, 3623–3634, <https://doi.org/10.5194/acp-25-3623-2025>, 2025.

Bednarz, EW, AH Butler, X Wang, Z Zhou, W Yu, G Stenchikov, M Toohey, Y Zhu (2025) Indirect climate impacts of the Hunga eruption. Preprint, <https://doi.org/10.5194/egusphere-2025-1970>

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identify a decadal mode of atmosphere–ocean variability in the North Atlantic with a dominant time scale of 13–18 years. Large-scale atmospheric circulation anomalies drive SST anomalies both through contemporaneous air–sea heat fluxes and through delayed ocean circulation changes, the latter involving both the meridional overturning circulation and the horizontal gyre circulation.

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**From:** Roy Spencer [roywspencer@hotmail.com]  
**Sent:** 5/18/2025 4:30:44 PM  
**To:** Judith Curry [curry.judith@cfanclimate.com]; John Christy [climateman60@gmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: new text: declining planetary albedo  
**Attachments:** Declining planetary albedo-RS-edits.docx

I made several edits... One being the reason why decreasing albedo is even being mentioned: record global-average warmth.

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**Sent:** Sunday, May 18, 2025 10:42 AM  
**To:** John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
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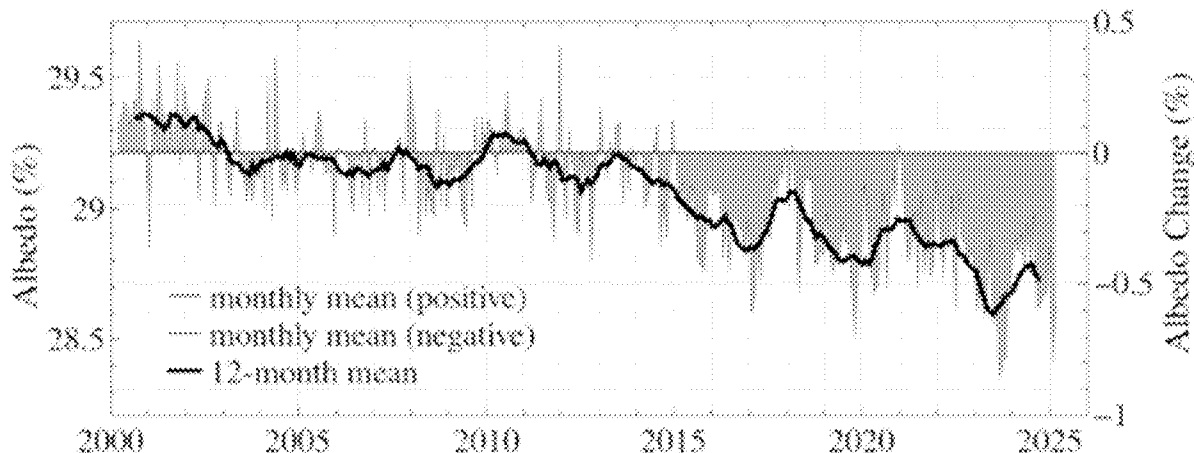


Figure xxx. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

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Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

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Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. In terms of pollution aerosol, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog et al., 2024; Yuan et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb et al., 2024; Gosling et al 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the northern hemisphere, whereas in the southern hemisphere the decrease in planetary albedo is primarily from decreases in mid-level clouds across all latitude zones. Gosling et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was the strongest El Nino event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).
- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019
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Interannual cloud anomalies associated with the El Niño Southern Oscillation (ENSO), which have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gossling et al. (2025) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz et al, 2025; Kuchar et al., 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO<sub>2</sub>. While it is difficult to untangle causes of the trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming, or a temporary fluctuation driven by natural variability

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Bednarz, EW, AH Butler, X Wang, Z Zhou, W Yu, G Stenchikov, M Toohey, Y Zhu (2025) Indirect climate impacts of the Hunga eruption. Preprint, <https://doi.org/10.5194/egusphere-2025-1970>

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identify a decadal mode of atmosphere–ocean variability in the North Atlantic with a dominant time scale of 13–18 years. Large-scale atmospheric circulation anomalies drive SST anomalies both through contemporaneous air–sea heat fluxes and through delayed ocean circulation changes, the latter involving both the meridional overturning circulation and the horizontal gyre circulation.

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**From:** Judith Curry <curry.judith@cfanclimate.com>  
**Sent:** Sunday, May 18, 2025 11:43 AM  
**To:** John Christy; Roy W. Spencer; Ross McKittrick; Steven Koonin; Travis Fisher  
**Subject:** new text: declining planetary albedo  
**Attachments:** Declining planetary albedo.docx

Ross suggested I write a section on the declining planetary albedo, for the attribution chapter. I'm sending the text for your comments before inserting into the chapter, since it is new material and I'm not sure how much of this we should actually include. In particular, I think Roy could be helpful here. Look forward to your comments.

## Declining planetary albedo

Planetary albedo is the fraction of incoming solar radiation that is reflected back into space by the Earth's surface and atmosphere. Earth's planetary albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is reflected back to space.

Arguably the most striking change to the Earth's climate system in the 21<sup>st</sup> century is a significant reduction in planetary albedo since 2015. Figure xxx shows the planetary albedo variations since 2000, when we have good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m<sup>2</sup> increase of solar energy averaged over the planet (Hansen and Karecha, 2025). For reference, doubling of CO<sub>2</sub> has a direct radiative impact of about 1.2 W/m<sup>2</sup>.

Looking back prior to 2000 with less adequate data, Gossling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before industrial aerosol precursor emissions led to global dimming until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1992. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.

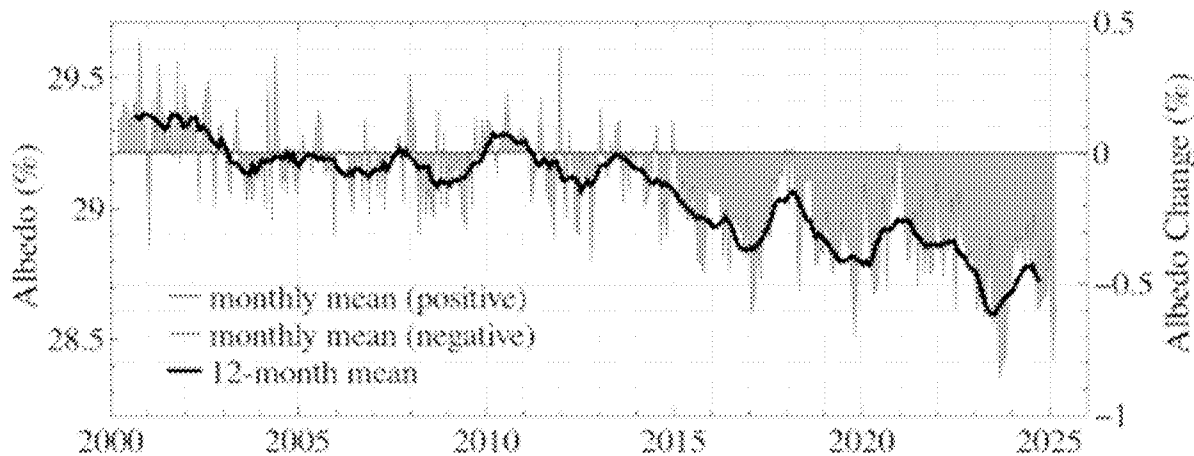


Figure xxx. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface characteristics can't explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5% since 1980 ([https://nsidc.org/data/seaice\\_index/images/s\\_plot\\_hires.png](https://nsidc.org/data/seaice_index/images/s_plot_hires.png)), although following 2007 there has been a pause in the Arctic sea ice decline (England et al., 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (SPM, A.1.5)
- Northern hemispheric snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer.  
<http://climate.rutgers.edu/snowcover/>
- Global greening (Chapter 2) is contributing the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase

cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Wednesday, May 21, 2025 10:18 AM  
**To:** Ross McKittrick; John Christy; Roy Spencer; Travis Fisher; Steve Koonin  
**Subject:** ch 8 earth 20th century warming  
**Attachments:** ch 8 nat var text.docx

New text for the natural variability section is attached

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### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, including the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulations influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, most models show too little power relative to observations at multi-decadal frequencies and phasing out-of-sync with the observed climate (Kravtsov et al. 2024). Averaging multiple simulations effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

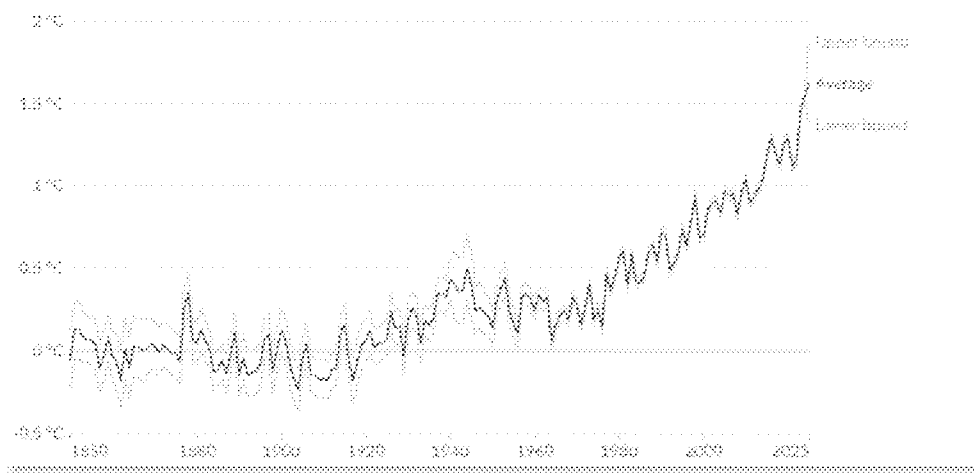
“Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.” (IPCC, 2013)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The time series of global surface temperature anomalies since 1850 shows irregular variations of significant amplitude against the background of an overall warming trend. The period between 1905-1945 shows a strong trend of warming. The following thirty years from 1945-1976 showed slightly declining temperatures. The most recent warming period started in 1977.



**Figure 8.1** Global average surface temperature.

The causes of the early 20<sup>th</sup> century warming is discussed by Hegerl et al. (2017; 2019). The atmospheric CO<sub>2</sub> concentration increased from 298 ppm in 1905 to 310 ppm in 1941; hence this implies that the early increase in CO<sub>2</sub> had a small impact on the warming. Volcanic activity during this period was very low, and solar forcing is uncertain. Hegerl et al (2017) somehow inferred that 40-54% of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman et al (2024) focused on the causes of the cooling in the first decade of the 20<sup>th</sup> century in the Southern Hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable.

The warming in the 1930's and subsequent cooling during mid century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that most likely these variations were caused by a combined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity as well as growing greenhouse gases concentrations. Tokinaga et al (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic warming in the early 20<sup>th</sup> century. The synchronized Pacific-Atlantic warming drastically alters planetary-scale over the Northern Hemisphere. These same circulation patterns have a global influence.

The cooling period between 1945 and 1976 has been referred to as the “grand hiatus.” Numerous causes for the cooling have been hypothesized: natural internal variability from fluctuations associated with the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation;

cooling from increased emissions of aerosols from industrial activities; increased heat uptake in the Atlantic, Southern and Equatorial Pacific Oceans. Thompson et al. (2010) find that the hemispheric differences in temperature trends in the middle of the twentieth century stem largely from a rapid drop in Northern Hemisphere sea surface temperatures of about 0.3 °C between about 1968 and 1972.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40 percent or more of the warming in the second half of the 20<sup>th</sup> century is attributed to natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

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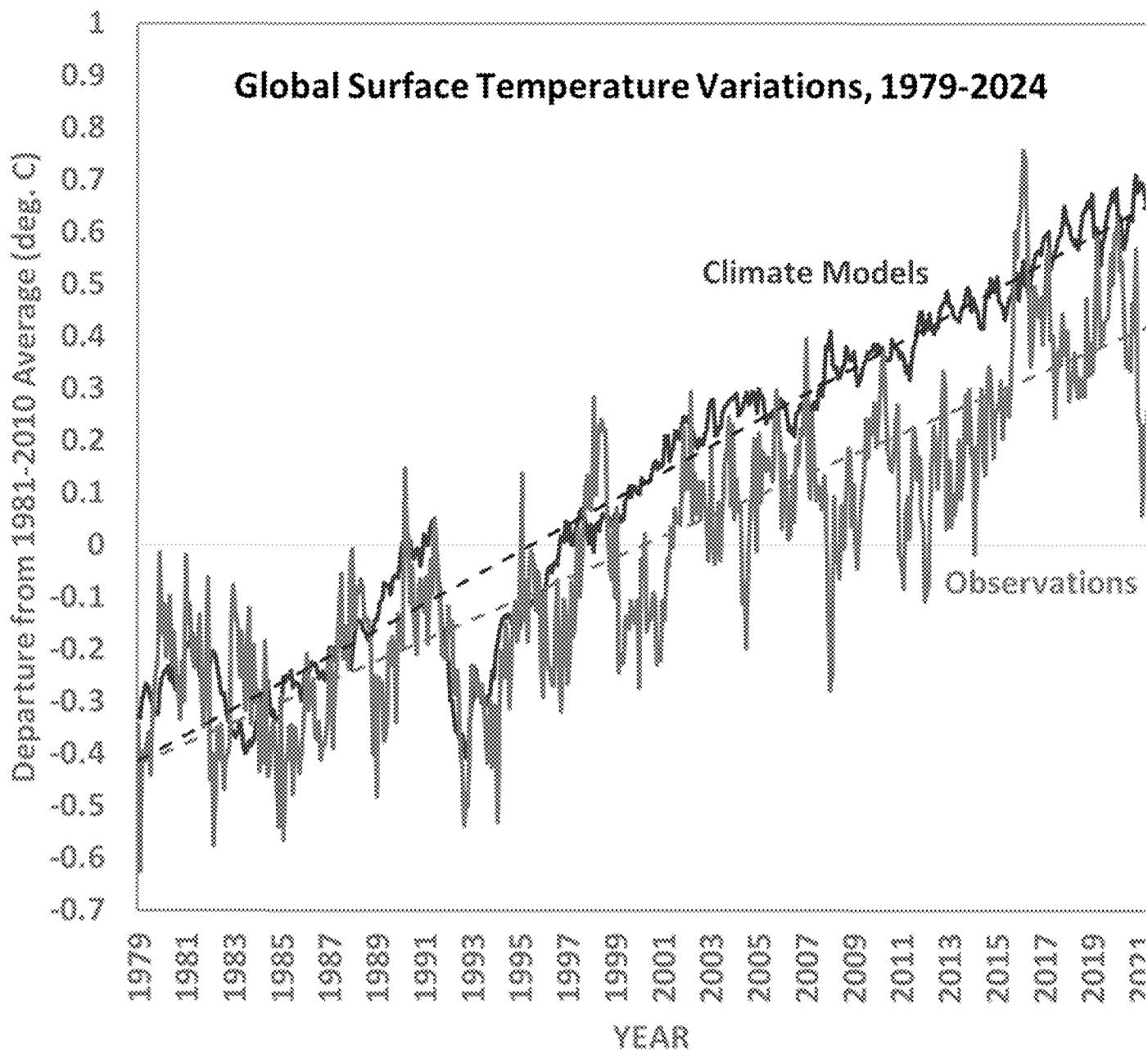
Thompson, DJW, M Wallace, J Kennedy, P Jones (2010) An abrupt drop in Northern Hemisphere sea surface temperature around 1970. Nature.

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Wednesday, May 21, 2025 8:51 AM  
**To:** Roy Spencer  
**Cc:** Steve Koonin; Judith Curry; John Christy; Travis Fisher  
**Subject:** Re: Fig. 5.3, updated through 2024  
**Attachments:** image.png

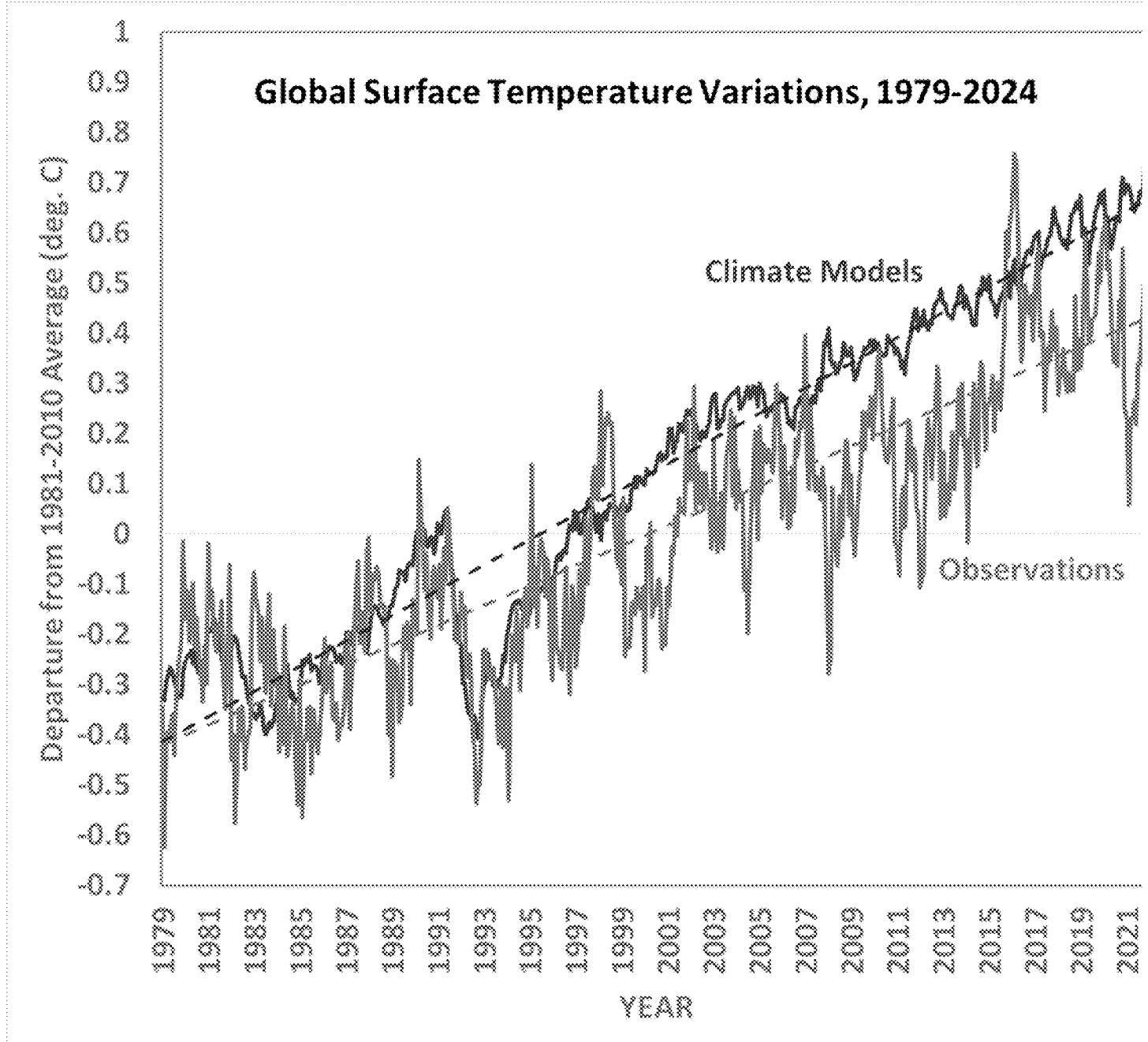
Thanks Roy I copied it into the post-meeting draft.  
Ross

On Wed, May 21, 2025 at 8:21 AM Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)> wrote:  
This took a while, I had to download all the different datasets again. The format is different because the placeholder we've been using was from the Heritage Foundation graphics folks



**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Wednesday, May 21, 2025 8:21 AM  
**To:** Ross McKittrick  
**Cc:** Steve Koonin; Judith Curry; John Christy; Travis Fisher  
**Subject:** Fig. 5.3, updated through 2024  
**Attachments:** paste.png

This took a while, I had to download all the different datasets again. The format is different because the placeholder we've been using was from the Heritage Foundation graphics folks



DOJ 00041901

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383.5 1697.5 431.5 1698.5 442.5 1700.5 386.5 1701.5 368.5 1703.5 375.5 1704.5 430.5  
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388.5 1768.5 321.5 1769.5 374.5 1771.5 351.5 1772.5 372.5 1774.5 357.5 1775.5 279.5  
1776.5 312.5 1778.5 352.5 1779.5 351.5 1780.5 337.5 1782.5 336.5 1783.5 333.5 1784.5  
291.5 1786.5 311.5 1787.5 277.5 1789.5 274.5 1790.5 267.5 1791.5 302.5 1793.5 296.5  
1794.5 333.5 1795.5 369.5 1797.5 366.5 1798.5 371.5 1799.5 324.5 1801.5 345.5 1802.5  
287.5 1804.5 401.5 1805.5 409.5 1806.5 469.5 1808.5 408.5 1809.5 408.5 1810.5 395.5  
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1830.5 363.5 1831.5 357.5 1832.5 345.5 1834.5 305.5 1835.5 395.5 1836.5 367.5 1838.5  
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1847.5 240.5 1849.5 160.5 1850.5 188.5 1851.5 172.5 1853.5 192.5 1854.5 240.5 1855.5  
205.5 1857.5 224.5 1858.5 234.5 1860.5 260.5 1861.5 256.5 1862.5 248.5 1864.5 222.5  
1865.5 231.5 1866.5 198.5 1868.5 212.5 1869.5 234.5" stroke="#0070C0" stroke-width="3"  
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fill="none"></path></g><g clip-path="url(#clip5)"><path d="M0 0 752 414" stroke="#C00000"  
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1117.5 639.5)"></path></g><g clip-path="url(#clip6)"><path d="M0 0 752 326"  
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stroke-miterlimit="10" stroke-dasharray="8 10.6667" fill="none" fill-rule="evenodd"  
transform="matrix(1 0 0 -1 1117.5 641.5)"></path></g><g clip-path="url(#clip7)"><text

DOJ 00041906

DOJ 00041907

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transform="matrix(6.12323e-17 -1 1 6.12323e-17 1045.67 444)">-</text></g><g clip-
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serif" font-weight="700" font-size="24" transform="matrix(6.12323e-17 -1 1 6.12323e-17
1045.67 436)">2010 Average (deg. C)</text></g><g clip-path="url(#clip51)"><text
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fill="none"></rect><g clip-path="url(#clip52)"><text font-
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transform="translate(1181.96 184)">Global Surface Temperature Variations,
1979</text></g><g clip-path="url(#clip53)"><text font-
family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="27"
transform="translate(1679.83 184)">-</text></g><g clip-path="url(#clip54)"><text font-
family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-size="27"
transform="translate(1688 184)">2024</text></g><g clip-path="url(#clip55)"><text
fill="#FF0000" font-family="Calibri,Calibri_MSFontService,sans-serif" font-weight="700" font-
size="24" transform="translate(1504.51 311)">Climate Models</text></g><g clip-
path="url(#clip56)"><text fill="#0070C0" font-family="Calibri,Calibri_MSFontService,sans-
serif" font-weight="700" font-size="24" transform="translate(1671.8
524)">Observations</text></g></svg>

```

**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/20/2025 12:28:18 AM  
**To:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'Judith Curry' [curry.judith@gmail.com]; 'John Christy' [climatemanager60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** paleo CO2 figure  
**Attachments:** image001.png; Paleo CO2.pptx; Paleo CO2.pdf

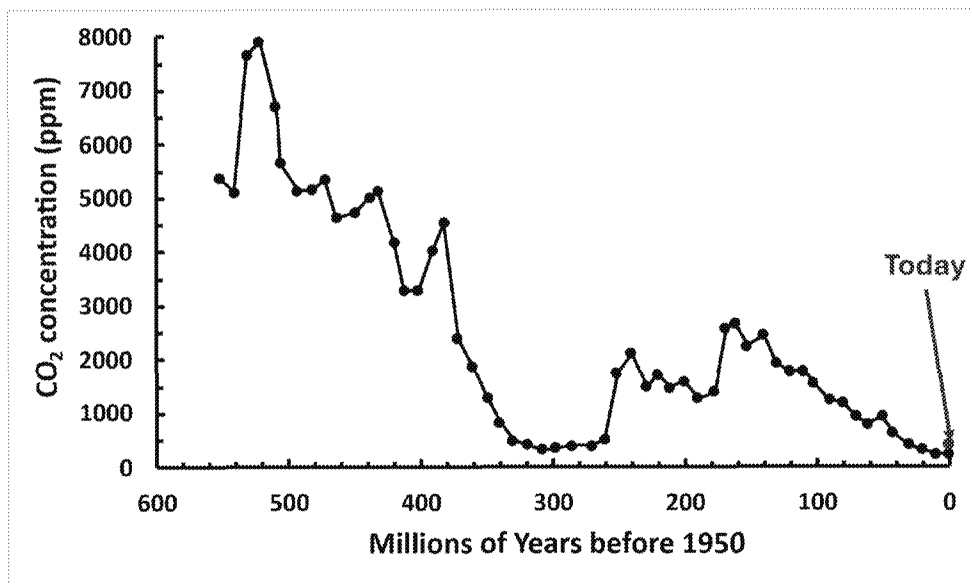
Pasted below is a revision of the paleo CO2 figure (also attached as ppt and pdf files)

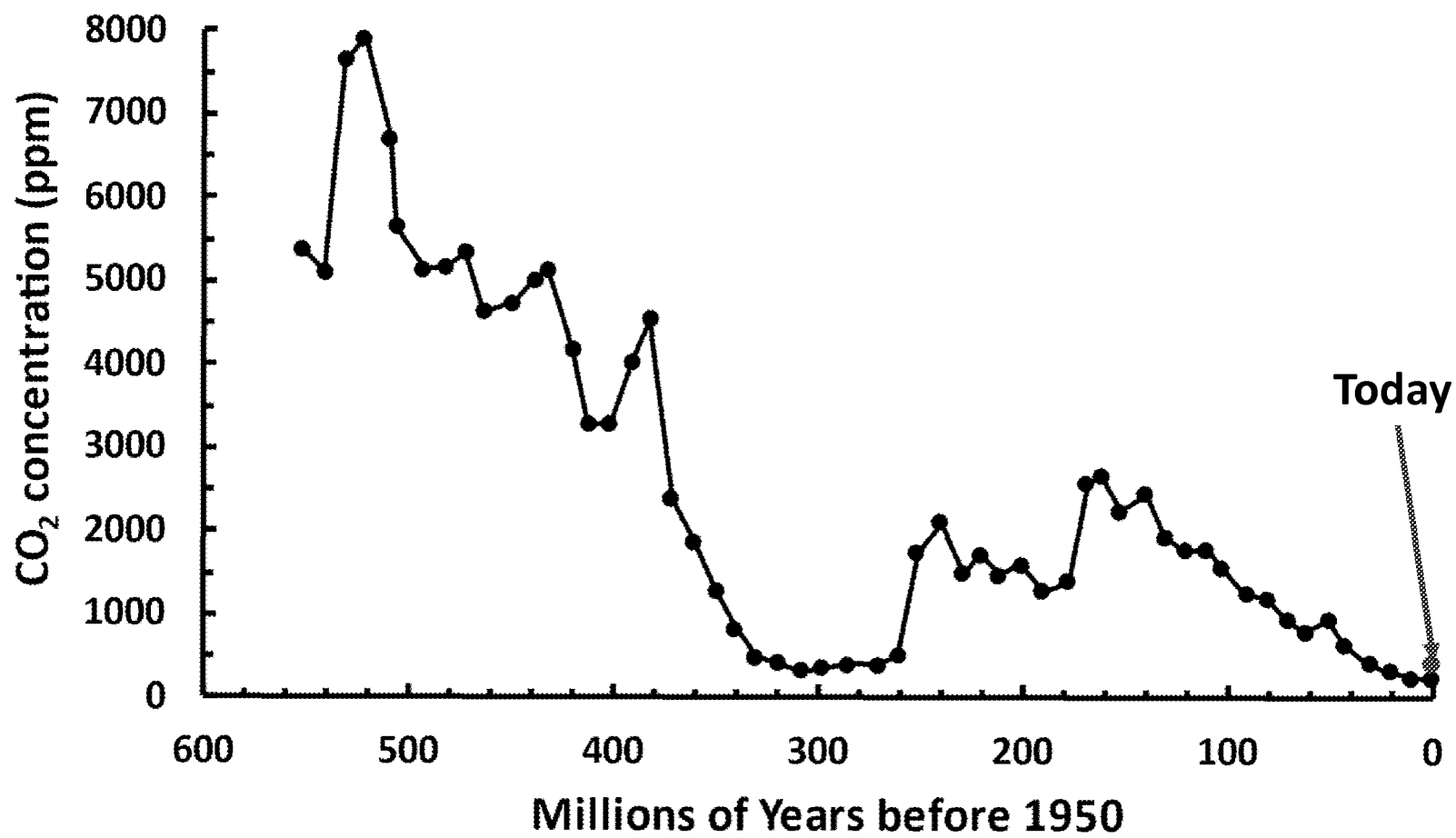
I've converted the previous ratios into absolute concentrations using the source's recommend 300 ppm scale.

The caption should be:

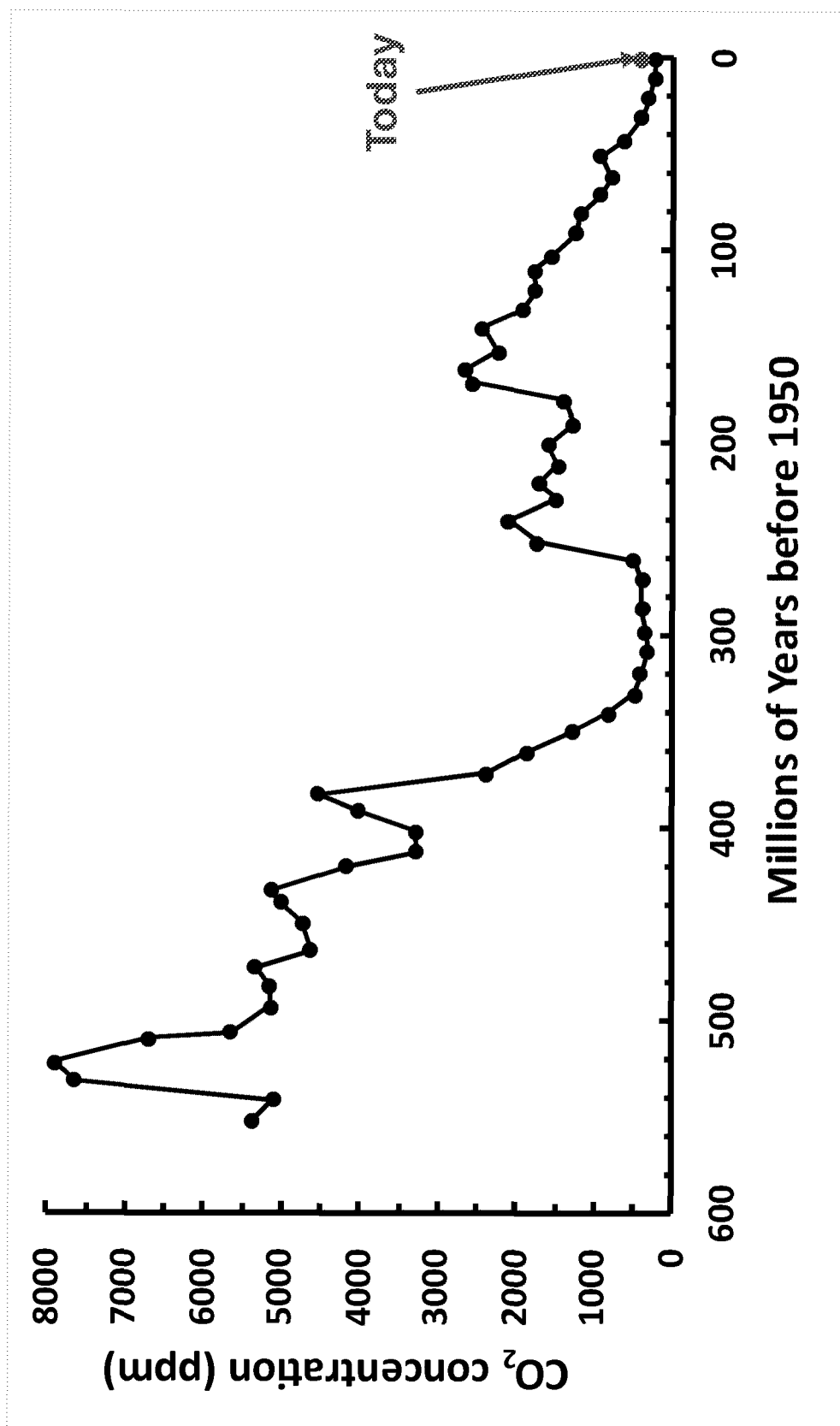
**Figure 2.2.** Ambient CO<sub>2</sub> levels over the past 550 million years. Today's concentration of 430 ppm is also shown. Source: (Berner 2006)

SEK









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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Monday, May 19, 2025 4:26 AM  
**To:** Ross McKittrick; Judith Curry; Travis Fisher; John Christy; Steven Koonin  
**Subject:** Re: urbanization bias

This looks good to me.  
-Roy

---

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Sunday, May 18, 2025 7:33 PM  
**To:** Judith Curry <curry.judith@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>  
**Subject:** urbanization bias

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Sunday, May 18, 2025 11:39 PM  
**To:** John Christy  
**Cc:** Judith Curry; Travis Fisher; Roy W. Spencer; Steve Koonin  
**Subject:** Re: urbanization bias

This would be a good place to make that point. Can you add a few sentences and a reference? Just put them in an email and I can paste it in. As I recall Dick McNider has a good paper on this.  
Ross

On Sun, May 18, 2025 at 9:54 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:  
Ross

Nice summary of how the IPCC ignored evidence. Is this the place to discuss the asymmetric impact of UHI and other aspects?, i.e. TMin much greater than TMax for physical reasons published as early as Oke 1973? Or is this a focussed description of the type of misdirection for which the IPCC is famous?

John C.

John Christy  
Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
[climateman60@gmail.com](mailto:climateman60@gmail.com)

On May 18, 2025, at 7:59 PM, Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:

I like it

On Sun, May 18, 2025 at 5:33 PM Ross McKittrick <[ross.mckitrick@gmail.com](mailto:ross.mckitrick@gmail.com)> wrote:

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Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>

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**From:** John Christy <climateman60@gmail.com>  
**Sent:** Sunday, May 18, 2025 9:54 PM  
**To:** Judith Curry  
**Cc:** Ross McKittrick; Travis Fisher; Roy W. Spencer; Steve Koonin  
**Subject:** Re: urbanization bias

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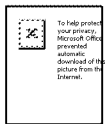
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---

**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Sunday, May 18, 2025 9:00 PM  
**To:** Ross McKittrick  
**Cc:** Travis Fisher; John Christy; Roy W. Spencer; Steven Koonin  
**Subject:** Re: urbanization bias

I like it

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---

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Sunday, May 18, 2025 8:33 PM  
**To:** Judith Curry; Travis Fisher; John Christy; Roy W. Spencer; Steven Koonin  
**Subject:** urbanization bias

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---

**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Tuesday, May 20, 2025 10:11 AM  
**To:** Ross McKitrick  
**Cc:** Roy Spencer; Steven Koonin; judith curry; John Christy  
**Subject:** Re: update

This is great, thanks Ross!

Are there any chapters that are final in terms of substantive content? I'd like to start fleshing out the template as soon as possible.

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**CONFIDENTIAL DRAFT FOR DISCUSSION PURPOSES**

Climate Analysis Group  
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Steven Koonin, Ph.D.  
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Suggested citation:

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**Sent:** Monday, May 19, 2025 5:14 PM  
**To:** Ross McKitrick  
**Cc:** Steven Koonin; judith curry; John Christy; Roy Spencer  
**Subject:** Re: update

How was the marathon review?

Ross, would you share the report template you want to use? Josh and I will start adding near-final material as soon as we get the green light from this group.

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## 6 Models versus Observations in the Recent Past

### 6.1 Introduction

Climate models are the primary tool used to project future climate changes in response to increasing atmospheric levels of anthropogenic greenhouse gases. They provide theoretical evidence underpinning energy policy changes, such as efforts to reduce carbon dioxide emissions. To assess the fitness of climate models for this purpose, it is reasonable to ask how well they reproduce the current climate and its variations over the past century. The nearby box “Climate modeling” gives some detail on how climate models work.

Of great concern is the fact that, after several decades of the climate modeling enterprise involving approximately three dozen models operated by research centers around the world, the range of future warming they produce in response to a hypothetical doubling of atmospheric CO<sub>2</sub> extends over a factor of three, as we discussed in the previous chapter. This range of disagreement among models has not changed for decades.

Problems with climate models are not just in their disagreement over the future, but also in their ability to replicate the recent past. Here we review some of the most important metrics of climate model accuracy: ability to reproduce historical surface, tropospheric and stratospheric temperature trends, ability to reproduce the vertical warming profile and ability to reproduce other climate features such as snowfall and humidity. In all cases a persistent finding is that models on average err on the side of too much warming in response to observed historical forcings.

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#### Box: Climate modeling

All but the simplest computer models of the climate begin by covering the earth’s land surface with a grid of squares, typically 100 km on a side. To describe the atmosphere, 10-20 layers of grid boxes are stacked above those squares. With a similar, but finer, grid covering the ocean, the model comprises one million grid boxes for the atmosphere and 100 million grid boxes for the ocean.

The computer models use the fundamental laws of physics to calculate how the air, water, and energy in each box at a given time move to neighboring grid boxes at a slightly later time; this time step can be as small as 10 minutes. Repeating this process millions of times simulates the climate for centuries, a calculation that can take months of computer time on even the most powerful supercomputers. Comparing the results of computer runs with what we know about past climates gives some sense of how good a model is. Calculations into the future under assumed human and natural influences then purport to describe the climate decades hence.

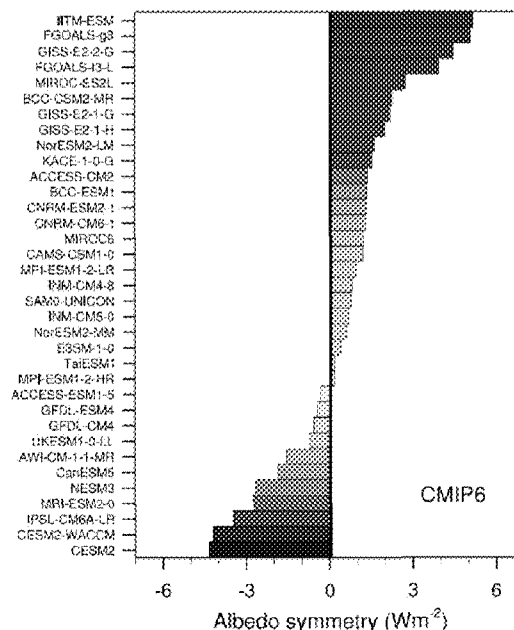
Unfortunately, while all this might sound straightforward, it isn’t. A major problem is that many important phenomena are much smaller than the 100 km grid size. For example, flows of sunlight and heat through the atmosphere are influenced by clouds. Because there are far too many clouds to follow each in detail, researchers must make “subgrid” assumptions about the number and type of clouds in each grid box to build a complete model. Cloud cover is only one among dozens of subgrid assumptions. Another is *How much snow or ice is on the surface?*, which controls the heating effect of sunlight.

Each subgrid assumption has numerical parameters that must be set, somehow. Modelers determine subgrid parameters based on what they know about physics and weather and climate observations and then run the model. Since the results generally don’t much look like the climate system we

observe, modelers adjust (“tune”) these parameters to better match some features of the real climate system. Different modelers will make different assumptions with different tunings and so produce widely different results.

Tuning is a necessary, but perilous, part of modeling the climate, as it is in modeling of any complex system. An ill-tuned model will be a poor description of the real world, while overtuning risks cooking the books— that is, predetermining the answer. For example, a [paper](#) laying out the details one of the most esteemed models, that of Germany’s Max Planck Institute, tells of tuning a subgrid parameter (related to convection in the atmosphere) by a factor of ten because the value chosen originally resulted in twice as much warming as had been observed.

To extract useful information from vastly different models, results are usually quoted as averages over a collection (“ensemble”) of models; the most recent UN IPCC assessments used the CMIP6 ensemble. The diversity of that ensemble is already evident in one of the simplest descriptions of the climate – the earth’s average surface temperature. It varies across the ensemble by about 3°C, three times greater than the observed warming during the 20th century. And the models differ just as significantly when you start to look at the details of their results. For example, since you’re not allowed to tune the freezing temperature of water (as it’s determined by Nature), the amounts of snow and ice cover might be very different for models with different surface temperatures. That can be seen in the [figure](#) below, which shows the differences between the sunlight absorbed by the Northern and Southern hemispheres for the CMIP6 models. It is disturbing that the range is large compared both to the observed value and to current human influences (about 2.5 Wm<sup>-2</sup>).



Caption: Differences in the reflectivity (albedo) between the Northern and Southern Hemispheres for members of the model ensemble used in the most recent IPCC assessment. The very small observed difference is indicated by the vertical black line.

While it would be reassuring if the models were able to accurately describe the current climate, the crucial issue for society how well they describe the *response* of the climate to physically small human influences such as warming greenhouse gases, cooling aerosols, and changes in land use. Here, the most important thing that a model has to get right are “feedbacks.” Here’s how feedbacks work. The growing greenhouse gas concentrations that raise the global temperature can also cause other

changes in the climate system that either amplify or suppress their direct warming influence. For example, as the globe gets warmer, there'll be less snow and ice on the surface, which decreases the planet's reflectivity. The less reflective earth will then absorb more sunlight, causing even more warming. Other important feedbacks involve the amount of water vapor and clouds in the atmosphere or the temperature profile of the atmosphere. The average of results over the many different models in the ensembles suggests that the net effect of all feedbacks is to double or triple CO<sub>2</sub>'s direct warming influence.

## **End BOX**

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### **6.2 Surface warming**

A straightforward test of a climate model's validity is its ability to reproduce historical warming in response to known past changes in climate drivers such as greenhouse gases. Figure 6.1 is reproduced from Scaffeta (2023), a peer-reviewed study that groups the latest-generation (CMIP6) climate models into low ECS (1.5 to 3.0 degrees C), medium ECS (3.0 to 4.5 degrees C) and high ECS (4.5 to 6.0 degrees C), and compares their post-1980 global average temperature simulation ranges to those of three surface temperature records and one satellite-based lower troposphere temperature data product.

The leftmost column shows that the low-ECS models track the post-1980 historical warming record reasonably well, but the middle and right columns show that the medium- and high-ECS models conspicuously over-predict the warming.

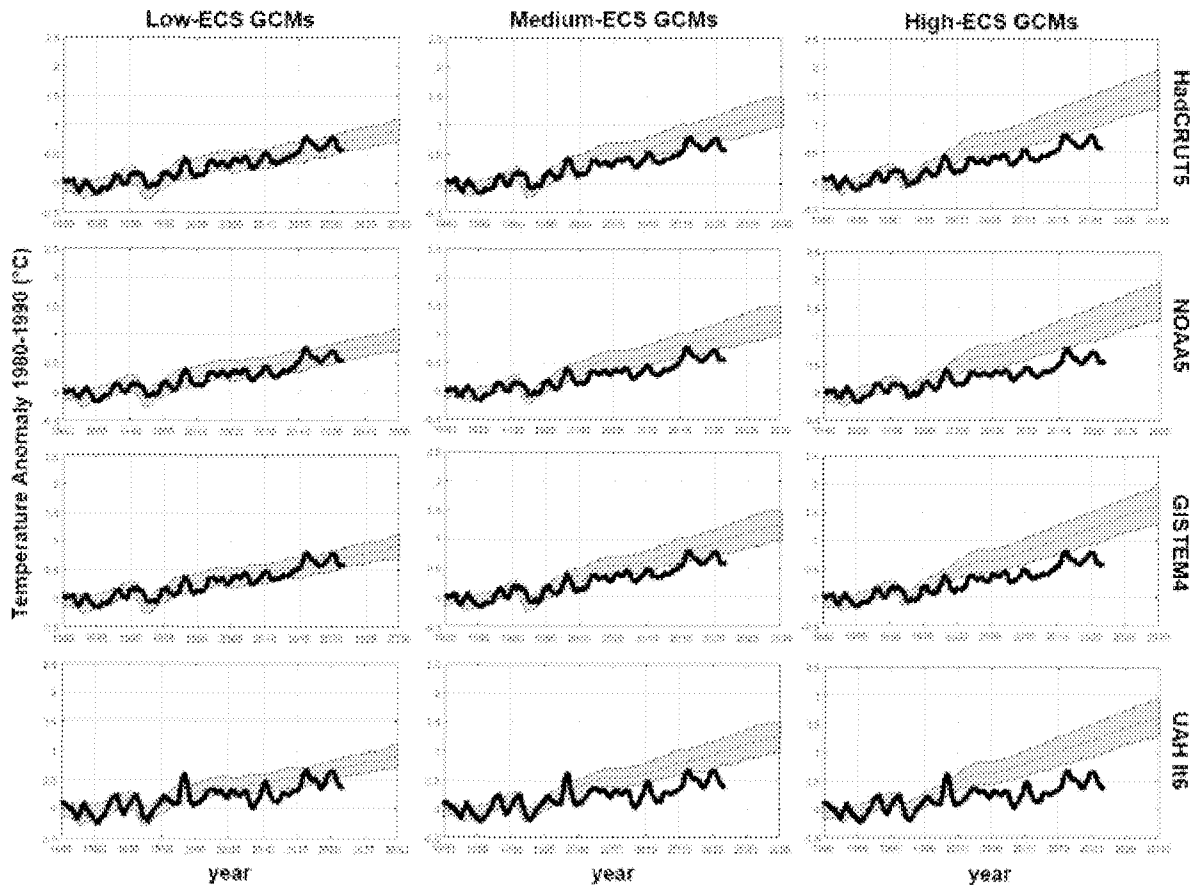


Figure 6.1: model-observational comparisons for Earth's surface warming. The columns correspond to model groups showing low-ECS to high-ECS, while the rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range ( $\pm$  one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated source.

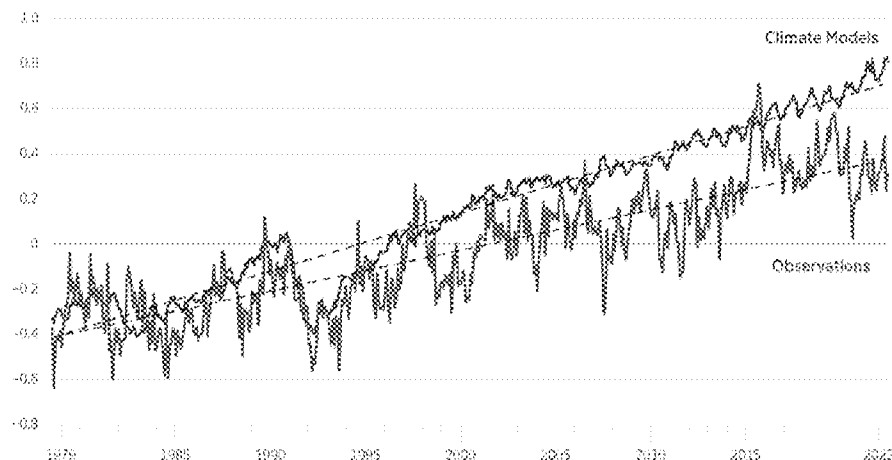
Source: Scafetta N. Climate Dynamics 2023 Fig.2.

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing average surface temperature data products with the average climate model warming, as summarized in Figure 6.2.

CHART 1

## Global Average Surface-Air Temperature Variations, 1979~2022

DEPARTURE FROM 1951-2020 AVERAGE, IN DEGREES CELSIUS



**NOTE:** Figures have been adjusted to align trends starting in 1979.

**SOURCES:** Authors' calculations based on data from five different observation-based datasets and 35 climate models taking part in the sixth IPCC Climate Model Intercomparison Project, and KNMI Climate Explorer, "Starting Point," <https://climate.knmi.nl/Start.asp> (accessed January 10, 2024).

Figure 6.2: Models versus observations at the surface. Source: Spencer (2024)

### 6.3 Tropospheric warming

It has long been known that climate models on average overstate warming in the tropical troposphere. Since this region generates the bulk of atmospheric warming in a model it is important to get the trends right. The discrepancy was flagged as a serious inconsistency in the first US Climate Change Science Program report (Karl et al. 2006) and has been mentioned in every IPCC report since, but it has gotten worse over time, and the bias is now global. McKittrick and Christy (2020) compare tropospheric warming rates in CMIP6 climate models to observations from satellites, weather balloons and reanalysis systems (Figure 6.3). Every model overpredicts the observed warming trend in both Lower- and Mid-Troposphere layers, both globally and in the tropics (Figure 6.4).

In most individual cases the bias is statistically significant and on average it is highly significant. McKittrick and Christy (2020) also show that the bias is larger in high-ECS models, but even the models with lower average ECS predict too much warming. If future models were to realistically represent global tropospheric warming, they would likely be less sensitive than even the low-ECS members of the CMIP6 ensemble

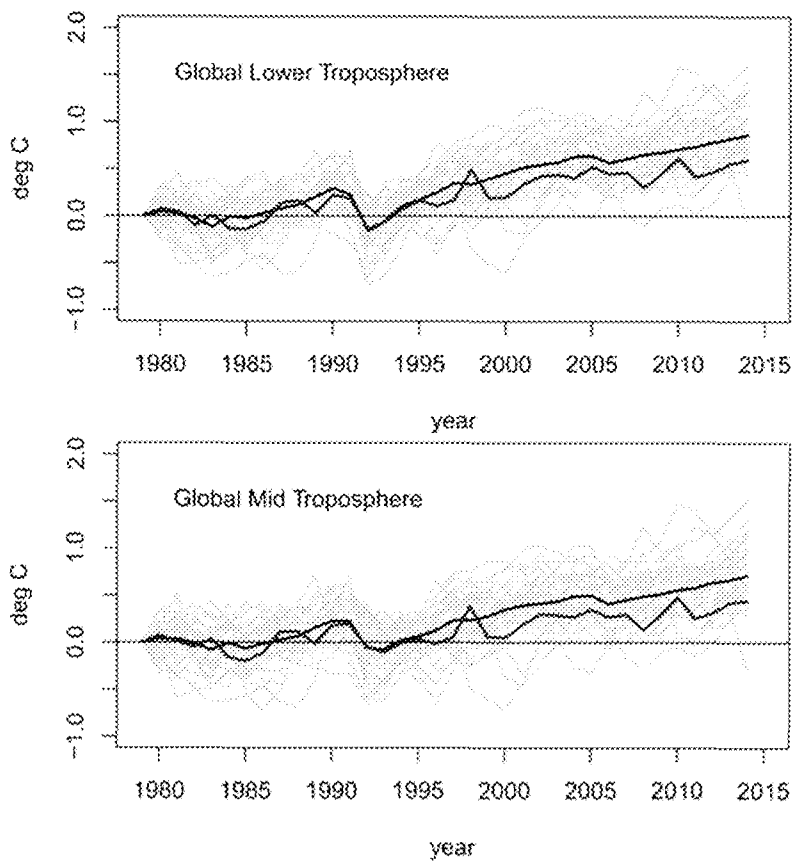


Figure 6.3: Models versus observations in the global troposphere. Source: McKittrick and Christy (2020). Gray lines: individual model runs. Black: average model run. Blue: average of satellite, radiosonde and reanalysis observations.



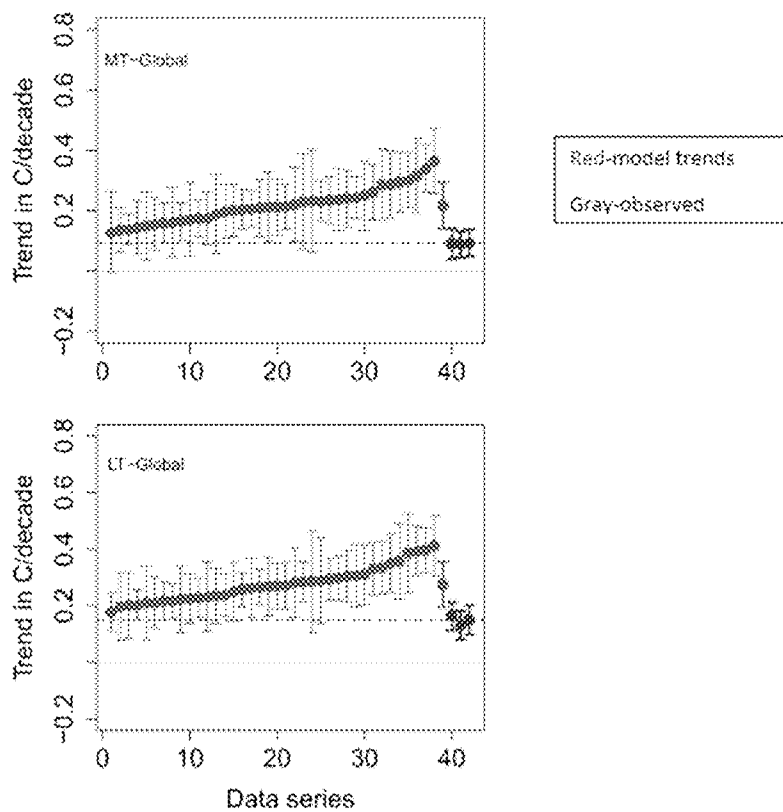


Figure 6.4: Modeled versus observed warming trends in the global troposphere. Adapted from McKittrick and Christy (2020). Red dots: model warming trend in  $^{\circ}\text{C}/\text{decade}$  with 95% confidence interval bars. Gray dots: observed warming trends in 3 data products (satellite, radiosondes and reanalysis) and 95% confidence interval bars.

Spencer (2024) shows the mismatch is also present in the lower troposphere:

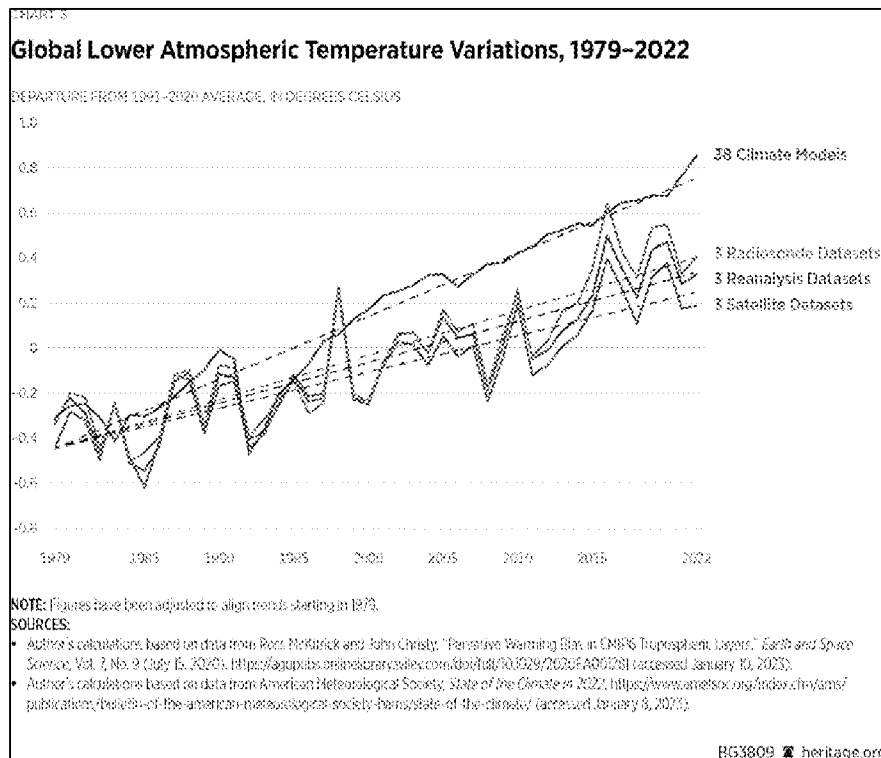


Figure 6.5: Comparison of average trends in lower troposphere, 1979-2022. Source: Spencer (2024).

As mentioned the IPCC has long acknowledged the model-observation mismatch. For example AR6 pp. 443-444 offers this on the tropical troposphere (it does not address the global comparison):

Several studies since AR5 have continued to demonstrate an inconsistency between simulated and observed temperature trends in the tropical troposphere, with models simulating more warming than observations (Mitchell et al., 2013, 2020; Santer et al., 2017a, b; McKittrick and Christy, 2018; Po-Chedley et al., 2021)... Over the 1979–2014 period, models are more consistent with observations in the lower troposphere, and least consistent in the upper troposphere around 200 hPa, where biases exceed 0.1°C per decade. Several studies using CMIP6 models suggest that differences in climate sensitivity may be an important factor contributing to the discrepancy between the simulated and observed tropospheric temperature trends (McKittrick and Christy, 2020; Po-Chedley et al., 2021), though it is difficult to deconvolve the influence of climate sensitivity, changes in aerosol forcing and internal variability in contributing to tropospheric warming biases (Po-Chedley et al., 2021). Another study found that the absence of a hypothesized negative tropical cloud feedback could explain half of the upper troposphere warming bias in one model (Mauritsen and Stevens, 2015).

... In summary, studies continue to find that CMIP5 and CMIP6 model simulations warm more than observations in the tropical mid- and upper-troposphere over the 1979–2014 period (Mitchell et al., 2013, 2020; Santer et al., 2017a, b; Suárez-Gutiérrez et al., 2017; McKittrick and Christy, 2018), and that overestimated surface warming is partially responsible (Mitchell et al., 2013; Po-Chedley et al., 2021). .... Hence, we assess with *medium confidence* that CMIP5

and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade,

Notably, despite the accumulation of evidence of excess model warming the IPCC only assigns *medium confidence* to the existence of a warming bias.

#### 6.4 Vertical profile mismatch and excess amplification

Another important model-observational discrepancy is the excess amplification with altitude found in climate models. A comparison was shown in the IPCC AR5 Chapter 10, although only in the online supplement. The diagram, reproduced below as Figure 6.6, compares temperature trends by altitude between models and observations for separate latitude bands.

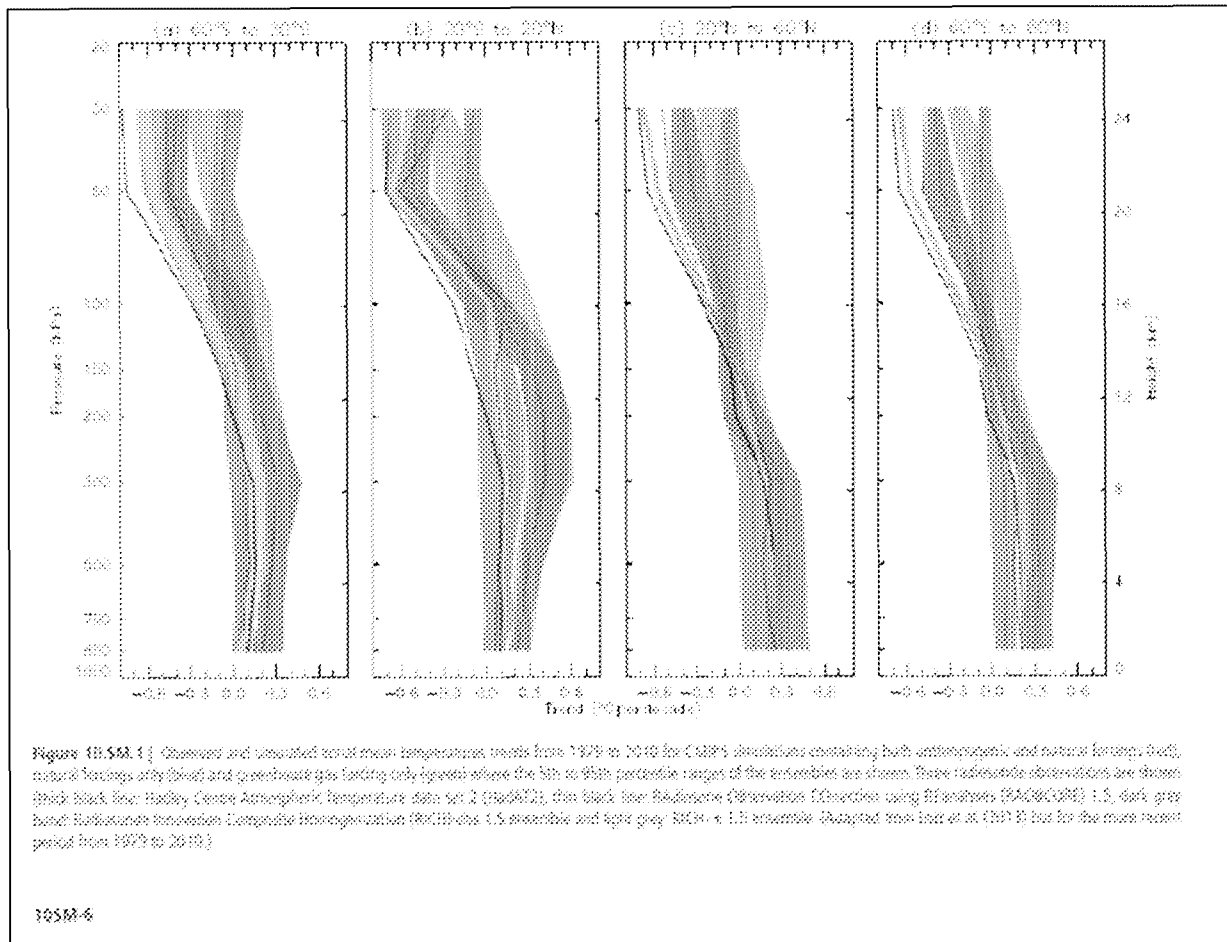


Figure 6.6: Vertical warming pattern by latitude band. Source: IPCC AR5 Figure 10.SM.1

The Figure is not referenced in the main report nor in any summary. Although not apparent at first glance, it shows that the 1979-2010 warming in the lower troposphere is so small as to be consistent with no GHG forcing at all, and is inconsistent with the model runs that do have GHG forcing. Here is the main global band (60S to 60N) expanded with the observed trends highlighted in yellow:

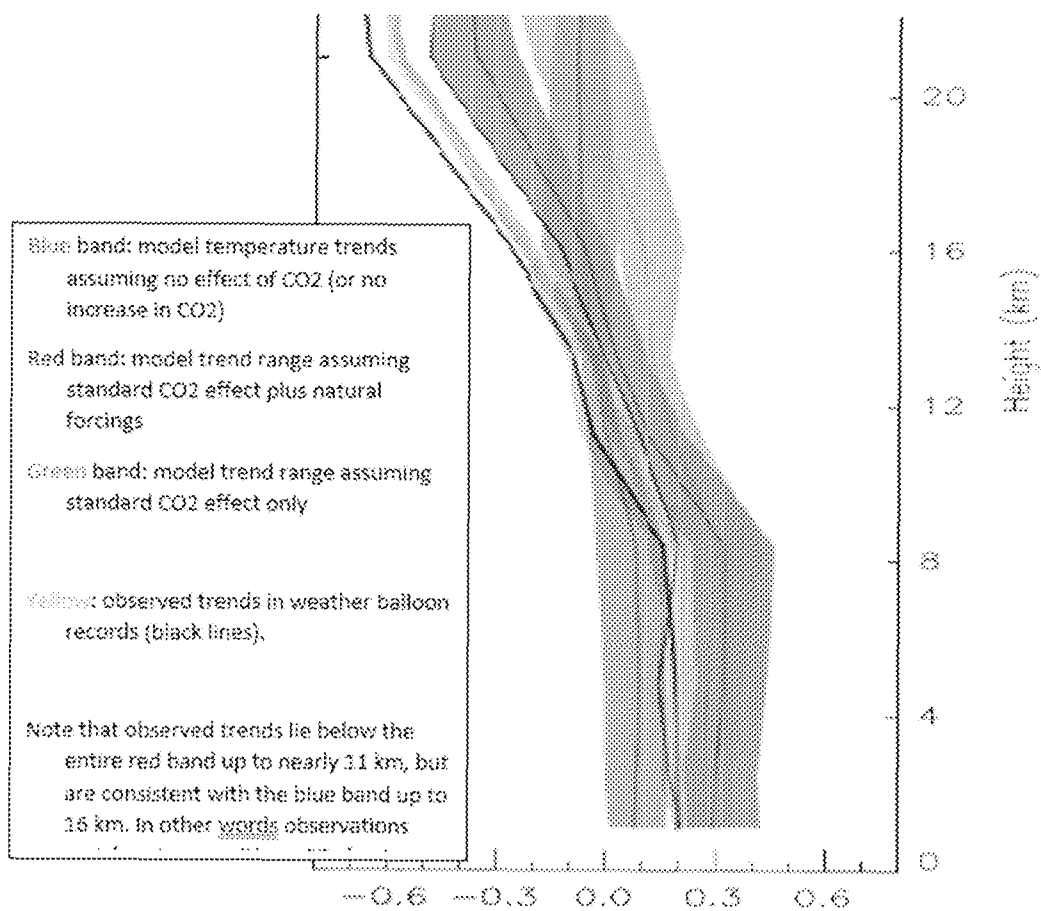


Figure 6.7: Adapted from IPCC AR5 Figure 10.SM.1

The next version of the Figure draws further detail out of the tropics band:

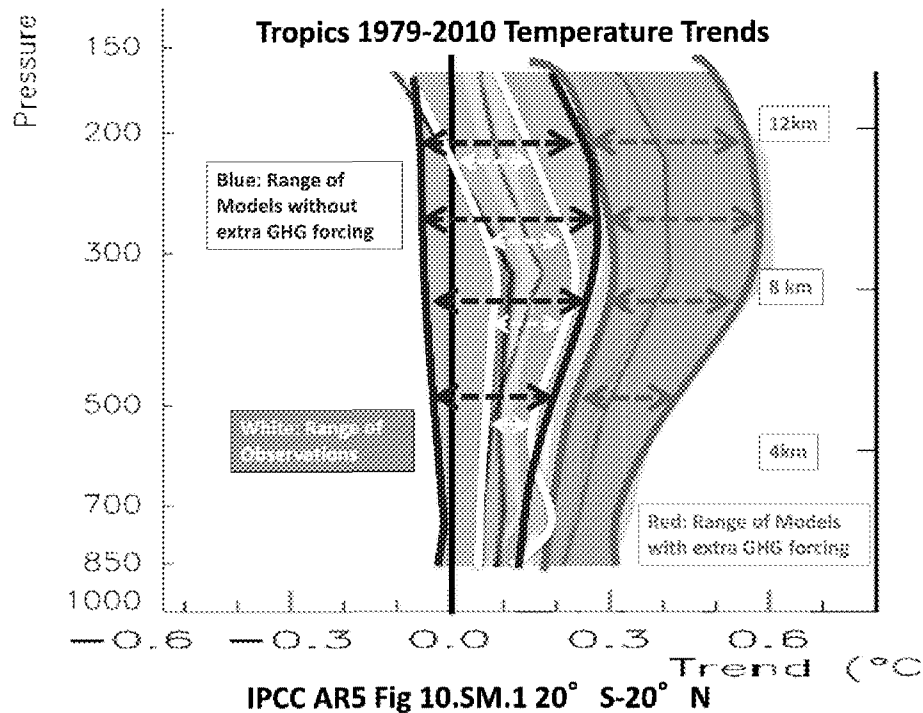


Figure 6.8: Adapted from IPCC AR5 Figure 10.SM.1.

In the tropics, where the models say the warming should be strongest, the observations (shown here in white) lie within the “No CO<sub>2</sub>” band and entirely outside the “with CO<sub>2</sub>” red envelope. This means that in the entire tropical atmospheric column from the surface to the stratosphere, *observed warming trends are so small they are consistent with the output of models that have no CO<sub>2</sub> warming effect in them, and they are inconsistent with the entire envelope of warming trends generated by models forced with increased CO<sub>2</sub>.*

A similar comparison is shown in Christy and McNider (2017), an updated version of which (covering 1979-2024) is reproduced as Figure 6.9. Modeled temperature trends exceed balloon observations from the surface through the top of the troposphere, with observed trends below the entire model range at most pressure levels. Also shown in Figure 6.9 is the TTT layer average from three satellite data products (NOAA, UAH and RSS) compared to the same layer average from climate models for 1979-2024. Again the observed trends lie below the entire model range.

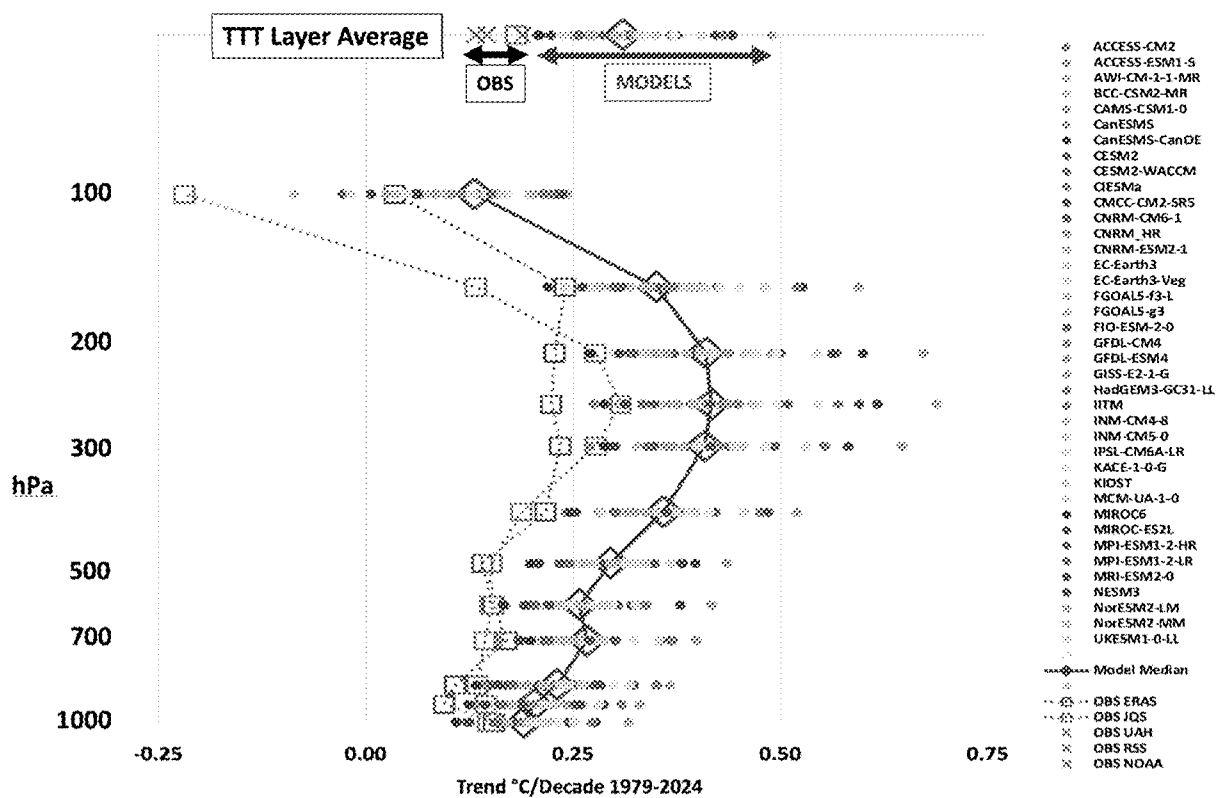


Figure 6.9: Modeled versus observed warming, tropical troposphere. Source: Christy and McNider (2017).

Some defenders of the models have argued that even if there is very little observed warming aloft in the tropics, a “hotspot” still exists in the sense that the warming aloft is greater than at the surface. But there is good evidence that models also exaggerate the amplification rate. Klotzbach et al. (2009), which was not discussed in the AR6, showed that models project greater amplification with altitude than is observed. That paper gave rise to an online debate over whether the amplification rates were being correctly calculated, and whether the discrepancy between models and observations was statistically significant. The topic involves very advanced statistical theory and was dealt with by two experts in time series analysis (Vogelsang and Nawaz 2016) who found that Klotzbach’s conclusions were valid, and that observed amplification is significantly smaller than the model-projected rates. The IPCC AR6 made no mention of this work either.

## 6.5 Stratospheric cooling

An important element of the expected general “fingerprint” of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. The IPCC AR6 acknowledged that cooling had been observed but only up to the year 2000. Thereafter the stratosphere has exhibited some warming, contrary to model projections.

The AR6 WG1 Ch 2 pp. 327-9 states (emphasis added):

“Temperatures averaged through the full lower stratosphere (roughly 10–25 km) have decreased over 1980–2019 in all data products, with **the bulk of the decrease prior to 2000**. The decrease holds even if the influence of the El Chichon (1982) and Pinatubo (1991) volcanic eruptions on the trend, found by Steiner et al. (2020a) to have increased the 1979–2018 cooling trend by 0.06°C per decade, is removed. **Most datasets show no significant or only marginally significant trends over 2000–2019, and the results of Philipona et al. (2018) show weak increases over 2000–2015** in the very lowermost stratosphere sampled by radiosondes....

It is virtually certain that the lower stratosphere has cooled since the mid-20th century. However, most datasets show that **lower stratospheric temperatures have stabilized since the mid-1990s with no significant change over the last 20 years**. It is likely that middle and upper stratospheric temperatures have decreased since 1980, but there is low confidence in the magnitude.

The cited source, Philipona et al. (2018), in an article entitled “Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming”, stated:

“In response to continued greenhouse gas increases and stratospheric ozone depletion, climate **models project continued tropospheric warming and stratospheric cooling** over the coming decades. Global average satellite observations of **lower stratospheric temperatures exhibit no significant trends since the turn of the century**. In contrast, an analysis of vertically resolved radiosonde measurements from 60 stations shows an increase of lower stratospheric temperature since the turn of the century at altitudes between 15 and 30 km and over most continents. Trend estimates are somewhat sensitive to homogeneity assessment choices, but all investigated **radiosonde data sets suggest a change from late twentieth century cooling to early 21st century warming in the lower stratosphere.**”

## 6.6 Water vapour trends mismatch

Much of the warming in climate models derives not from GHG increases themselves but from water vapour feedbacks: extra warming induced by the projected accumulation of water vapour in the atmosphere after it warms due to CO<sub>2</sub>. But new evidence (Simpson et al. 2024) shows that models have over-projected increases in humidity.

“Water vapor in the atmosphere is expected to rise with warming because a warmer atmosphere can hold more moisture. However, over the last four decades, **near-surface water vapor has not increased over arid and semi-arid regions**. This is **contrary to all climate model simulations** in which it rises at a rate close to theoretical expectations, even over dry regions. This may indicate a major model misrepresentation of hydroclimate-related processes; **models increase water vapor to satisfy the increased atmospheric demand, while this has not happened in reality.**”

(Simpson et al. 2024)

While the models and observations matched over the 1988 to 2006 interval they diverge after that, directly contradicting model projections.

## 6.7 Snow cover mismatch

Data compiled by the Rutgers University Snow Lab (undated) show that Northern Hemisphere winter snow cover is not decreasing. If anything, shows an increasing trend:.

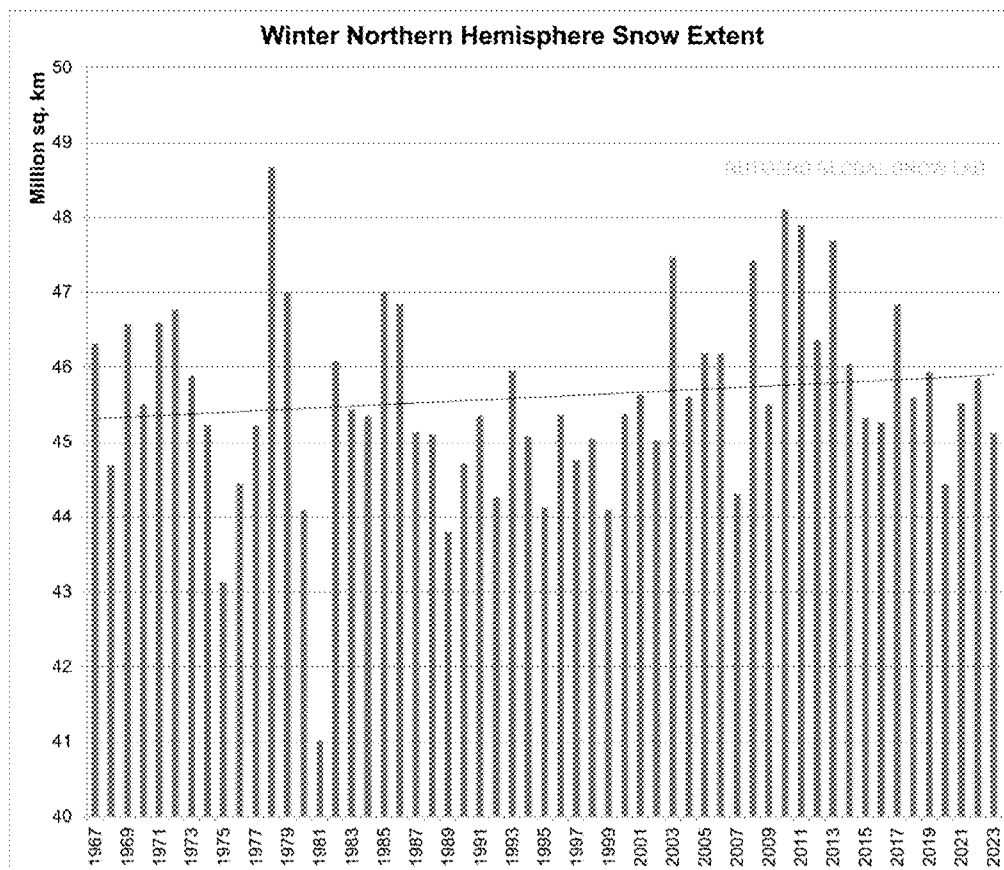


Figure 6.10: Northern Hemisphere Winter Snow extent. Source: [https://climate.rutgers.edu/snowcover/chart\\_seasonal.php?ui\\_set=nhland&ui\\_season=1](https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1) (February 24, 2024)

Yet models project declining Northern Hemisphere snow cover due to climate warming, as described by Connolly et al. (2019).

The climate models were found to poorly explain the observed trends [in Northern Hemisphere snow cover]. While the models suggest snow cover should have steadily decreased for all four seasons, only spring and summer exhibited a long-term decrease, and the pattern of the observed decreases for these seasons was quite different from the modelled predictions. Moreover, the observed trends for autumn and winter suggest a long-term increase, although these trends were not statistically significant. Connolly et al. (2019).

## 6.8 US Corn Belt

One of the largest discrepancies between models and observations is in the U.S. Corn Belt, a region of particular importance to global food production. Figure 6.11 shows the warming trends for summertime (June, July, August) for the 12-state Corn Belt (IN, IA, NE, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).





To summarize:

- 15

As has been noted by two leaders of the modeling community,  
... for many key applications that require regional climate model output or for assessing large-scale changes from smallscale processes, we believe that **the current generation of models is not fit for purpose.** - T. Palmer and B. Stevens, PNAS (2019)

---

**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Sunday, May 18, 2025 4:54 PM  
**To:** Steven Koonin  
**Cc:** Ross McKittrick; judith curry; John Christy; Roy Spencer  
**Subject:** Re: update

I agree with Ross that the central point made in Chapter 1 (that CO2 is not directly harmful to humans at ambient concentrations) is a big one. That said, the last paragraph of Chapter 1 functions a bit like an introduction, so maybe we could parse these out and keep a stand-alone chapter on the main point while moving the last P of Chapter 1 to the introduction? It reads:

The growing amount of CO2 in the atmosphere directly influences the earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and also by neutralizing ocean alkalinity. But the primary concern about CO2 is its role as a greenhouse gas (GHG), that alters the earth's energy balance. How the climate will respond to that influence is a complex question that will occupy much of this report.

Chapter 2 then discusses the "direct impacts" of CO2 on the environment, namely global greening and reduced ocean alkalinity. To the untrained reader (people like me), it might seem like you all are distinguishing between temperature and non-temperature impacts (or energy and non-energy impacts), and that you deem temperature impacts to be distinct from "direct" impacts. I note this for two reasons: 1) if that wasn't the intent, perhaps you could add some clarity in the introduction, and 2) if that was the intent, you could explain why you're saving the warming/RF for later discussion. (Most people expect to see the big-ticket item up front.)

If temperature change / RF is a direct impact, I'd recommend saying something like "we note three broad categories of direct impacts from increased CO2 concentrations: global greening, reduced alkalinity of the oceans, and increased radiative forcing. We touch on the first two briefly in Chapter 2 before discussing anthropogenic radiative forcing in Chapter 3. Then we take a deeper look at the climate's response to increased CO2 concentrations in Chapters 4 through X [Part 2]." [You could also set up Part 3 in the introduction and explain how you see the different parts of the report as covering different themes.]

On Sun, May 18, 2025 at 4:32 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

On the preface: First, technically it's not a foreword, which is front matter written by a non-author (in this case, the Secretary). A "preface" is something written by the authors (us). Both of them are distinct from the Introduction (guess we all know what that is).

I'd like our foreword to be a more personal statement, incorporating some of the material now in the section called "Intro". I'll come back with a draft of that tomorrow. But I'd note now that I'd like it welcome community response, both to simulate an open dialog and to model behavior missing from IPCC/NCA/...

Meanwhile, I think the material now in Chap 1 would work very well as the ending of the Introduction.

SEK

---

**From:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>  
**Sent:** Sunday, May 18, 2025 4:22 PM  
**To:** judith curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Cc:** Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>; Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>  
**Subject:** Re: update

I like chapter 1 on its own even though it's very brief. I don't think the material fits anywhere else and it makes an important point.

On Sun, May 18, 2025 at 4:12 PM judith curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:

I think we should lose chapter 1 and incorporate in preface

Sent from my iPhone

On May 18, 2025, at 12:44 PM, Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

I've now been through almost all the May15 chapters in the 01.Report Draft folder.

My comments/edits on each are in the files in the "Final Comments" Dropbox folder.

Many of my suggested edits are aimed at clarifying and tightening language, but some are substantial.

I've done little in those chapters I've reviewed before, but there's a lot in others where I've not yet had a chance to weigh in.

A major missing yet is the Model v Observations chapter, which I'll get to before we start tomorrow.

Also will weigh in on the new albedo and emissions text and offer something about the Preface

SEK

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**Cc:** 'John Christy'; 'Travis Fisher'; 'Roy Spencer'  
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**Sent:** Sunday, May 18, 2025 4:12 PM  
**To:** Steven Koonin  
**Cc:** John Christy; Travis Fisher; Roy Spencer; ross.mckitrick@gmail.com  
**Subject:** Re: update

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**Sent:** Sunday, May 18, 2025 3:45 PM  
**To:** 'Judith Curry'; 'John Christy'; 'Travis Fisher'; 'Roy Spencer'; ross.mckitrick@gmail.com  
**Subject:** update

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SEK

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**From:** John Christy [climateman60@gmail.com]  
**Sent:** 5/21/2025 2:48:38 PM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]  
**CC:** Judith Curry [curry.judith@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Steve Koonin [steven.koonin@gmail.com]  
**Subject:** Re: Model-obs comparison in troposphere  
**Attachments:** CMIP6\_20250521\_Ross.xlsx

Ross

Here is the updated observations tab through 2024. Note this is 5 years to the day that I sent the data for the 2019 paper.

BE CAREFUL as I had to adjust the columns in the OBS tab to include NOAA satellite data and I eliminated ERA-I in a couple of places. So, make sure you are reading the correct columns

I do not trust the radiosondes for these values because (a) they are geographically deficient, especially in tropics and SH and (b) there are known biases that have yet to be corrected (e.g. the Vaisala software update in 2010 shifted tropospheric temperatures by 0.15°C upward - which is why their trends are warmer than the satellites). These radiosonde errors bleed into the reanalyses too, so the satellites are in general the most stable (though RSS still has yet to correct their spurious warming due to NOAA-14 drift.). UAH and NOAA data, though built in very different ways, are almost identical in trends.

John C.

On Tue, May 20, 2025 at 8:18 PM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

It needs to match the formatting of the attached: each model on a separate sheet, columns and rows positioned just so.

On Tue, May 20, 2025 at 9:12 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:  
Ross

I can reformat if you could send what you need.

John C.

Sent from my iPhone

On May 20, 2025, at 7:37 PM, Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

The updated data you sent are formatted very differently from the earlier spreadsheets and would take a lot of coding to get into the program.

On Tue, May 20, 2025 at 8:35 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

Oh, I see through 2018.

John Christy  
Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
[climateman60@gmail.com](mailto:climateman60@gmail.com)

On May 20, 2025, at 7:04 PM, Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

Is this better?

<image.png>

Figure 5.4: Observed versus modeled warming trends in the global lower (LT) and mid-troposphere (MT). Adapted from McKittrick and Christy (2020). Blue dots: warming trends ( $^{\circ}\text{C}/\text{decade}$  1979-2018) with 95% confidence interval bars for 3 data products (satellite, radiosondes and reanalysis) and 95% confidence interval bars. Blue dashed line: warming trend average for 3 observed series. Red dots: modeled warming trends in 36 models.

LT Global

|      | RAOBCOR | RICH17 | RATPAC | UAHv6.0 | RSSv4.0 | NOAA   | Avg Sat | ERA5   |
|------|---------|--------|--------|---------|---------|--------|---------|--------|
| 1958 | -0.444  | -0.528 | -0.513 |         |         |        |         | -0.395 |
| 1959 | -0.463  | -0.562 | -0.601 |         |         |        |         | -0.454 |
| 1960 | -0.508  | -0.612 | -0.619 |         |         |        |         | -0.571 |
| 1961 | -0.455  | -0.578 | -0.568 |         |         |        |         | -0.523 |
| 1962 | -0.614  | -0.727 | -0.706 |         |         |        |         | -0.613 |
| 1963 | -0.583  | -0.687 | -0.689 |         |         |        |         | -0.582 |
| 1964 | -0.710  | -0.810 | -0.933 |         |         |        |         | -0.755 |
| 1965 | -0.804  | -0.907 | -0.947 |         |         |        |         | -0.805 |
| 1966 | -0.640  | -0.736 | -0.721 |         |         |        |         | -0.560 |
| 1967 | -0.622  | -0.706 | -0.725 |         |         |        |         | -0.661 |
| 1968 | -0.766  | -0.859 | -0.797 |         |         |        |         | -0.724 |
| 1969 | -0.521  | -0.619 | -0.582 |         |         |        |         | -0.452 |
| 1970 | -0.489  | -0.545 | -0.577 |         |         |        |         | -0.507 |
| 1971 | -0.811  | -0.865 | -0.862 |         |         |        |         | -0.801 |
| 1972 | -0.625  | -0.689 | -0.685 |         |         |        |         | -0.616 |
| 1973 | -0.328  | -0.398 | -0.426 |         |         |        |         | -0.373 |
| 1974 | -0.720  | -0.767 | -0.783 |         |         |        |         | -0.783 |
| 1975 | -0.692  | -0.743 | -0.739 |         |         |        |         | -0.730 |
| 1976 | -0.860  | -0.931 | -0.922 |         |         |        |         | -0.860 |
| 1977 | -0.433  | -0.527 | -0.451 |         |         |        |         | -0.427 |
| 1978 | -0.440  | -0.532 | -0.545 |         |         |        |         | -0.490 |
| 1979 | -0.360  | -0.442 | -0.414 | -0.346  | -0.495  |        | -0.421  | -0.303 |
| 1980 | -0.213  | -0.287 | -0.275 | -0.178  | -0.344  |        | -0.261  | -0.235 |
| 1981 | -0.240  | -0.306 | -0.282 | -0.248  | -0.358  | -0.272 | -0.293  | -0.261 |
| 1982 | -0.466  | -0.530 | -0.518 | -0.433  | -0.560  | -0.393 | -0.462  | -0.466 |
| 1983 | -0.267  | -0.321 | -0.362 | -0.178  | -0.327  | -0.131 | -0.212  | -0.235 |
| 1984 | -0.533  | -0.586 | -0.567 | -0.374  | -0.590  | -0.402 | -0.455  | -0.504 |
| 1985 | -0.493  | -0.553 | -0.530 | -0.498  | -0.645  | -0.438 | -0.527  | -0.535 |
| 1986 | -0.403  | -0.481 | -0.487 | -0.356  | -0.528  | -0.274 | -0.386  | -0.413 |

|       |        |        |        |        |        |        |        |        |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1987  | -0.125 | -0.201 | -0.242 | -0.087 | -0.233 | 0.033  | -0.096 | -0.135 |
| 1988  | -0.112 | -0.160 | -0.196 | -0.098 | -0.264 | 0.012  | -0.117 | -0.090 |
| 1989  | -0.373 | -0.409 | -0.446 | -0.346 | -0.467 | -0.234 | -0.349 | -0.318 |
| 1990  | -0.085 | -0.113 | -0.210 | -0.124 | -0.290 | -0.015 | -0.143 | -0.065 |
| 1991  | -0.083 | -0.112 | -0.245 | -0.116 | -0.245 | 0.006  | -0.118 | -0.090 |
| 1992  | -0.414 | -0.447 | -0.512 | -0.417 | -0.518 | -0.289 | -0.408 | -0.376 |
| 1993  | -0.330 | -0.366 | -0.446 | -0.339 | -0.453 | -0.275 | -0.356 | -0.346 |
| 1994  | -0.266 | -0.297 | -0.293 | -0.201 | -0.318 | -0.152 | -0.224 | -0.255 |
| 1995  | -0.201 | -0.227 | -0.190 | -0.067 | -0.177 | -0.053 | -0.099 | -0.141 |
| 1996  | -0.324 | -0.343 | -0.369 | -0.146 | -0.278 | -0.156 | -0.193 | -0.246 |
| 1997  | -0.298 | -0.316 | -0.324 | -0.144 | -0.242 | -0.159 | -0.182 | -0.245 |
| 1998  | 0.232  | 0.220  | 0.155  | 0.347  | 0.224  | 0.306  | 0.292  | 0.220  |
| 1999  | -0.253 | -0.259 | -0.303 | -0.153 | -0.243 | -0.211 | -0.202 | -0.280 |
| 2000  | -0.284 | -0.291 | -0.326 | -0.157 | -0.248 | -0.221 | -0.208 | -0.315 |
| 2001  | -0.119 | -0.137 | -0.132 | -0.022 | -0.079 | -0.061 | -0.054 | -0.130 |
| 2002  | 0.016  | -0.006 | -0.031 | 0.080  | 0.033  | 0.035  | 0.049  | -0.001 |
| 2003  | 0.009  | -0.008 | 0.024  | 0.050  | 0.048  | 0.014  | 0.037  | -0.012 |
| 2004  | -0.088 | -0.091 | -0.081 | -0.056 | -0.024 | -0.088 | -0.056 | -0.104 |
| 2005  | 0.093  | 0.106  | 0.141  | 0.063  | 0.110  | 0.040  | 0.071  | 0.044  |
| 2006  | -0.017 | 0.000  | 0.065  | -0.023 | 0.020  | -0.044 | -0.016 | -0.035 |
| 2007  | 0.042  | 0.059  | 0.050  | 0.023  | 0.055  | 0.000  | 0.026  | 0.015  |
| 2008  | -0.254 | -0.239 | -0.199 | -0.238 | -0.153 | -0.250 | -0.214 | -0.240 |
| 2009  | -0.012 | -0.001 | 0.013  | -0.043 | 0.009  | -0.043 | -0.025 | -0.027 |
| 2010  | 0.140  | 0.151  | 0.233  | 0.194  | 0.254  | 0.197  | 0.215  | 0.250  |
| 2011  | -0.130 | -0.115 | -0.034 | -0.120 | -0.072 | -0.109 | -0.100 | -0.075 |
| 2012  | -0.059 | -0.044 | 0.022  | -0.084 | -0.006 | -0.084 | -0.058 | -0.035 |
| 2013  | 0.073  | 0.091  | 0.136  | -0.001 | 0.069  | 0.004  | 0.024  | 0.068  |
| 2014  | 0.117  | 0.138  | 0.167  | 0.044  | 0.127  | 0.056  | 0.075  | 0.113  |
| 2015  | 0.270  | 0.287  | 0.302  | 0.137  | 0.260  | 0.154  | 0.183  | 0.221  |
| 2016  | 0.595  | 0.610  | 0.554  | 0.388  | 0.456  | 0.389  | 0.411  | 0.499  |
| 2017  | 0.355  | 0.373  | 0.382  | 0.265  | 0.332  | 0.240  | 0.279  | 0.359  |
| 2018  | 0.249  | 0.268  | 0.264  | 0.088  | 0.193  | 0.101  | 0.127  | 0.233  |
| 2019  | 0.470  | 0.492  | 0.481  | 0.296  | 0.401  | 0.293  | 0.330  | 0.437  |
| 2020  | 0.475  | 0.505  | 0.495  | 0.351  | 0.465  | 0.361  | 0.392  | 0.495  |
| 2021  | 0.238  | 0.275  | 0.298  | 0.138  | 0.271  | 0.184  | 0.197  | 0.290  |
| 2022  | 0.267  | 0.228  | 0.320  | 0.15   | 0.254  | 0.192  | 0.199  | 0.300  |
| 2023  | 0.515  | 0.530  | 0.573  | 0.432  | 0.551  | 0.475  | 0.486  | 0.585  |
| 2024  | 0.860  | 0.875  | 0.924  | 0.774  | 0.860  | 0.784  | 0.806  | 0.914  |
| 2025  |        |        |        |        |        |        |        |        |
| 79-24 | 0.195  | 0.217  | 0.232  | 0.152  | 0.228  | 0.146  | 0.176  | 0.195  |
| 95-19 | 0.243  | 0.263  | 0.277  | 0.108  | 0.210  | 0.126  | 0.148  | 0.225  |

0.444  
0.405  
0.340  
0.374  
0.196  
0.207  
0.060  
-0.053  
0.091  
0.089  
-0.074  
0.152  
0.164



|        |        |        |
|--------|--------|--------|
| -0.178 |        |        |
| -0.011 |        |        |
| 0.267  |        |        |
| -0.145 |        |        |
| -0.137 |        |        |
| -0.323 |        |        |
| 0.083  |        |        |
| 0.057  |        |        |
| 0.117  | 0.102  | 0.160  |
| 0.245  | 0.235  | 0.276  |
| 0.199  | 0.194  | 0.246  |
| -0.047 | -0.051 | -0.014 |
| 0.132  | 0.136  | 0.119  |
| -0.153 | -0.151 | -0.108 |
| -0.132 | -0.140 | -0.095 |
| -0.062 | -0.089 | -0.075 |
| 0.196  | 0.168  | 0.147  |
| 0.190  | 0.188  | 0.170  |
| -0.091 | -0.083 | -0.103 |
| 0.178  | 0.191  | 0.109  |
| 0.160  | 0.171  | 0.051  |
| -0.190 | -0.186 | -0.239 |
| -0.126 | -0.127 | -0.196 |
| -0.081 | -0.079 | -0.066 |
| -0.035 | -0.031 | 0.014  |
| -0.179 | -0.169 | -0.188 |
| -0.172 | -0.164 | -0.167 |
| 0.338  | 0.350  | 0.289  |
| -0.166 | -0.150 | -0.192 |
| -0.217 | -0.204 | -0.238 |
| -0.071 | -0.072 | -0.068 |
| 0.044  | 0.038  | 0.011  |
| 0.018  | 0.014  | 0.042  |
| -0.099 | -0.091 | -0.086 |
| 0.063  | 0.084  | 0.113  |
| -0.066 | -0.043 | 0.014  |
| -0.027 | -0.006 | -0.024 |
| -0.342 | -0.326 | -0.296 |
| -0.120 | -0.110 | -0.107 |
| 0.012  | 0.020  | 0.090  |
| -0.277 | -0.267 | -0.201 |
| -0.226 | -0.218 | -0.168 |
| -0.113 | -0.105 | -0.077 |
| -0.089 | -0.080 | -0.069 |
| 0.045  | 0.047  | 0.043  |
| 0.351  | 0.350  | 0.271  |

|        |        |        |
|--------|--------|--------|
| 0.091  | 0.090  | 0.077  |
| -0.035 | -0.036 | -0.065 |
| 0.167  | 0.166  | 0.129  |
| 0.152  | 0.157  | 0.119  |
| -0.104 | -0.095 | -0.101 |
| -0.094 | -0.163 | -0.102 |
| 0.154  | 0.138  | 0.151  |
| 0.498  | 0.484  | 0.503  |

|        |        |           |         |            | LT Tropics   |        |        |
|--------|--------|-----------|---------|------------|--------------|--------|--------|
| JRA3Q  | MERRA  | Sonde Ave | Sat Avg | Reanal Avg | RAOBCOR RICH |        |        |
| -0.568 |        | -0.495    |         | -0.482     | 1958         | -0.215 | -0.368 |
| -0.658 |        | -0.542    |         | -0.556     | 1959         | -0.436 | -0.556 |
| -0.730 |        | -0.580    |         | -0.651     | 1960         | -0.398 | -0.558 |
| -0.711 |        | -0.533    |         | -0.617     | 1961         | -0.605 | -0.810 |
| -0.788 |        | -0.682    |         | -0.700     | 1962         | -0.610 | -0.808 |
| -0.738 |        | -0.653    |         | -0.660     | 1963         | -0.500 | -0.683 |
| -0.837 |        | -0.818    |         | -0.796     | 1964         | -0.623 | -0.809 |
| -0.909 |        | -0.886    |         | -0.857     | 1965         | -0.747 | -0.933 |
| -0.710 |        | -0.699    |         | -0.635     | 1966         | -0.430 | -0.611 |
| -0.795 |        | -0.685    |         | -0.728     | 1967         | -0.662 | -0.818 |
| -0.865 |        | -0.807    |         | -0.794     | 1968         | -0.671 | -0.858 |
| -0.580 |        | -0.574    |         | -0.516     | 1969         | -0.159 | -0.339 |
| -0.685 |        | -0.537    |         | -0.596     | 1970         | -0.193 | -0.230 |
| -0.939 |        | -0.846    |         | -0.870     | 1971         | -1.076 | -1.103 |
| -0.751 |        | -0.667    |         | -0.684     | 1972         | -0.469 | -0.537 |
| -0.552 |        | -0.384    |         | -0.462     | 1973         | -0.303 | -0.397 |
| -0.923 |        | -0.757    |         | -0.853     | 1974         | -0.902 | -0.978 |
| -0.870 |        | -0.725    |         | -0.800     | 1975         | -0.882 | -0.973 |
| -0.979 |        | -0.904    |         | -0.919     | 1976         | -0.829 | -0.981 |
| -0.585 |        | -0.471    |         | -0.506     | 1977         | -0.331 | -0.505 |
| -0.616 |        | -0.506    |         | -0.553     | 1978         | -0.294 | -0.442 |
| -0.405 |        | -0.405    | -0.421  | -0.354     | 1979         | -0.197 | -0.326 |
| -0.303 | -0.222 | -0.258    | -0.261  | -0.253     | 1980         | -0.127 | -0.243 |
| -0.337 | -0.268 | -0.276    | -0.293  | -0.289     | 1981         | -0.272 | -0.380 |
| -0.481 | -0.511 | -0.505    | -0.462  | -0.486     | 1982         | -0.340 | -0.448 |
| -0.268 | -0.315 | -0.317    | -0.212  | -0.273     | 1983         | -0.038 | -0.111 |
| -0.547 | -0.552 | -0.562    | -0.455  | -0.534     | 1984         | -0.544 | -0.597 |
| -0.566 | -0.600 | -0.525    | -0.527  | -0.567     | 1985         | -0.513 | -0.573 |
| -0.430 | -0.509 | -0.457    | -0.386  | -0.450     | 1986         | -0.321 | -0.422 |

|        |        |        |        |        |      |        |        |
|--------|--------|--------|--------|--------|------|--------|--------|
| -0.130 | -0.228 | -0.189 | -0.096 | -0.164 | 1987 | 0.126  | 0.034  |
| -0.105 | -0.138 | -0.156 | -0.117 | -0.111 | 1988 | -0.160 | -0.231 |
| -0.359 | -0.403 | -0.409 | -0.349 | -0.360 | 1989 | -0.581 | -0.637 |
| -0.119 | -0.185 | -0.136 | -0.143 | -0.123 | 1990 | -0.096 | -0.158 |
| -0.130 | -0.201 | -0.147 | -0.118 | -0.140 | 1991 | -0.067 | -0.138 |
| -0.408 | -0.464 | -0.458 | -0.408 | -0.416 | 1992 | -0.210 | -0.269 |
| -0.392 | -0.421 | -0.381 | -0.356 | -0.386 | 1993 | -0.236 | -0.284 |
| -0.265 | -0.292 | -0.285 | -0.224 | -0.270 | 1994 | -0.219 | -0.257 |
| -0.146 | -0.166 | -0.206 | -0.099 | -0.151 | 1995 | -0.047 | -0.078 |
| -0.231 | -0.272 | -0.346 | -0.193 | -0.250 | 1996 | -0.269 | -0.299 |
| -0.228 | -0.244 | -0.313 | -0.182 | -0.239 | 1997 | -0.144 | -0.192 |
| 0.260  | 0.221  | 0.202  | 0.292  | 0.234  | 1998 | 0.331  | 0.303  |
| -0.215 | -0.242 | -0.272 | -0.202 | -0.246 | 1999 | -0.532 | -0.539 |
| -0.243 | -0.249 | -0.301 | -0.208 | -0.269 | 2000 | -0.388 | -0.395 |
| -0.063 | -0.061 | -0.129 | -0.054 | -0.085 | 2001 | -0.173 | -0.198 |
| 0.033  | 0.078  | -0.007 | 0.049  | 0.037  | 2002 | 0.070  | 0.034  |
| 0.033  | 0.111  | 0.008  | 0.037  | 0.044  | 2003 | 0.067  | 0.036  |
| -0.049 | 0.034  | -0.087 | -0.056 | -0.040 | 2004 | -0.037 | -0.044 |
| 0.118  | 0.181  | 0.113  | 0.071  | 0.114  | 2005 | 0.131  | 0.158  |
| 0.018  | 0.058  | 0.016  | -0.016 | 0.013  | 2006 | -0.018 | 0.022  |
| -0.005 | 0.056  | 0.050  | 0.026  | 0.022  | 2007 | -0.056 | -0.015 |
| -0.252 | -0.172 | -0.231 | -0.214 | -0.221 | 2008 | -0.424 | -0.392 |
| -0.049 | -0.022 | 0.000  | -0.025 | -0.033 | 2009 | 0.095  | 0.123  |
| 0.223  | 0.186  | 0.174  | 0.215  | 0.220  | 2010 | 0.198  | 0.221  |
| -0.071 | -0.097 | -0.093 | -0.100 | -0.081 | 2011 | -0.341 | -0.312 |
| -0.036 | -0.050 | -0.027 | -0.058 | -0.041 | 2012 | -0.098 | -0.075 |
| 0.058  | 0.007  | 0.100  | 0.024  | 0.044  | 2013 | 0.052  | 0.080  |
| 0.092  | 0.074  | 0.140  | 0.075  | 0.093  | 2014 | 0.119  | 0.139  |
| 0.197  | 0.175  | 0.286  | 0.183  | 0.198  | 2015 | 0.333  | 0.346  |
| 0.463  | 0.427  | 0.587  | 0.411  | 0.463  | 2016 | 0.637  | 0.647  |
| 0.307  | 0.301  | 0.370  | 0.279  | 0.322  | 2017 | 0.311  | 0.331  |
| 0.172  | 0.188  | 0.260  | 0.127  | 0.198  | 2018 | 0.108  | 0.143  |
| 0.368  | 0.428  | 0.481  | 0.330  | 0.411  | 2019 | 0.424  | 0.463  |
| 0.433  | 0.434  | 0.491  | 0.392  | 0.454  | 2020 | 0.383  | 0.438  |
| 0.234  | 0.270  | 0.270  | 0.197  | 0.265  | 2021 | 0.013  | 0.085  |
| 0.282  | 0.341  | 0.272  | 0.199  | 0.308  | 2022 | -0.014 | -0.112 |
| 0.571  | 0.653  | 0.539  | 0.486  | 0.603  | 2023 | 0.502  | 0.581  |
| 0.884  | 0.973  | 0.886  | 0.806  | 0.924  | 2024 | 0.920  | 0.999  |
|        |        |        |        |        | 2025 |        |        |
| 0.198  | 0.216  | 0.215  | 0.176  | 0.202  |      | 0.155  | 0.190  |
| 0.182  | 0.183  | 0.261  | 0.148  | 0.197  |      |        |        |







| RATPAC | UAH    | RSS4.0 | NOAA   | ERA5   | JRA3Q  | MERRA-2 | Sonde Ave | Sat Avg |
|--------|--------|--------|--------|--------|--------|---------|-----------|---------|
| -0.098 |        |        |        | -0.215 | -0.357 |         | -0.227    |         |
| -0.488 |        |        |        | -0.487 | -0.625 |         | -0.493    |         |
| -0.489 |        |        |        | -0.570 | -0.691 |         | -0.482    |         |
| -0.707 |        |        |        | -0.686 | -0.812 |         | -0.707    |         |
| -0.631 |        |        |        | -0.680 | -0.761 |         | -0.683    |         |
| -0.576 |        |        |        | -0.598 | -0.661 |         | -0.586    |         |
| -0.715 |        |        |        | -0.750 | -0.750 |         | -0.716    |         |
| -0.884 |        |        |        | -0.776 | -0.802 |         | -0.855    |         |
| -0.471 |        |        |        | -0.443 | -0.532 |         | -0.504    |         |
| -0.730 |        |        |        | -0.771 | -0.804 |         | -0.737    |         |
| -0.637 |        |        |        | -0.726 | -0.793 |         | -0.722    |         |
| -0.264 |        |        |        | -0.205 | -0.269 |         | -0.254    |         |
| -0.398 |        |        |        | -0.417 | -0.503 |         | -0.274    |         |
| -1.007 |        |        |        | -1.008 | -1.099 |         | -1.062    |         |
| -0.570 |        |        |        | -0.466 | -0.540 |         | -0.525    |         |
| -0.306 |        |        |        | -0.305 | -0.444 |         | -0.335    |         |
| -0.868 |        |        |        | -0.928 | -1.000 |         | -0.916    |         |
| -0.884 |        |        |        | -0.921 | -1.000 |         | -0.913    |         |
| -0.921 |        |        |        | -0.849 | -0.937 |         | -0.910    |         |
| -0.436 |        |        |        | -0.388 | -0.495 |         | -0.424    |         |
| -0.422 |        |        |        | -0.428 | -0.505 |         | -0.386    |         |
| -0.252 | -0.359 | -0.293 |        | -0.148 | -0.238 |         | -0.258    | -0.326  |
| -0.159 | -0.228 | -0.210 |        | -0.165 | -0.234 | -0.214  | -0.176    | -0.219  |
| -0.271 | -0.359 | -0.378 | -0.330 | -0.333 | -0.378 | -0.371  | -0.308    | -0.356  |
| -0.369 | -0.372 | -0.405 | -0.278 | -0.373 | -0.349 | -0.437  | -0.386    | -0.352  |
| -0.055 | 0.029  | -0.045 | 0.147  | -0.018 | -0.020 | -0.162  | -0.068    | 0.044   |
| -0.538 | -0.443 | -0.565 | -0.439 | -0.552 | -0.570 | -0.674  | -0.560    | -0.482  |
| -0.557 | -0.585 | -0.686 | -0.483 | -0.603 | -0.605 | -0.758  | -0.548    | -0.585  |
| -0.452 | -0.346 | -0.463 | -0.235 | -0.400 | -0.387 | -0.581  | -0.398    | -0.348  |



|        |        |        |        |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 0.103  | 0.179  | 0.069  | 0.325  | 0.126  | 0.137  | -0.036 | 0.088  | 0.191  |
| -0.168 | -0.134 | -0.241 | -0.002 | -0.119 | -0.152 | -0.182 | -0.187 | -0.126 |
| -0.623 | -0.554 | -0.622 | -0.413 | -0.504 | -0.563 | -0.568 | -0.614 | -0.530 |
| -0.189 | -0.191 | -0.281 | -0.041 | -0.099 | -0.166 | -0.198 | -0.148 | -0.171 |
| -0.185 | -0.124 | -0.196 | 0.019  | -0.089 | -0.145 | -0.160 | -0.130 | -0.100 |
| -0.282 | -0.308 | -0.347 | -0.160 | -0.243 | -0.273 | -0.240 | -0.254 | -0.272 |
| -0.297 | -0.245 | -0.296 | -0.155 | -0.212 | -0.268 | -0.222 | -0.272 | -0.232 |
| -0.241 | -0.167 | -0.257 | -0.114 | -0.204 | -0.223 | -0.177 | -0.239 | -0.179 |
| -0.080 | 0.005  | -0.103 | 0.028  | -0.040 | -0.087 | -0.065 | -0.068 | -0.023 |
| -0.344 | -0.153 | -0.258 | -0.183 | -0.217 | -0.266 | -0.231 | -0.304 | -0.198 |
| -0.245 | -0.021 | -0.105 | -0.049 | -0.089 | -0.116 | -0.020 | -0.193 | -0.058 |
| 0.333  | 0.548  | 0.408  | 0.483  | 0.447  | 0.444  | 0.492  | 0.322  | 0.480  |
| -0.530 | -0.384 | -0.462 | -0.451 | -0.498 | -0.452 | -0.464 | -0.534 | -0.432 |
| -0.441 | -0.280 | -0.366 | -0.366 | -0.428 | -0.360 | -0.363 | -0.408 | -0.337 |
| -0.214 | -0.106 | -0.177 | -0.168 | -0.249 | -0.160 | -0.154 | -0.195 | -0.150 |
| 0.023  | 0.079  | 0.043  | 0.023  | -0.034 | 0.038  | 0.071  | 0.042  | 0.048  |
| 0.076  | 0.109  | 0.088  | 0.060  | 0.017  | 0.094  | 0.156  | 0.060  | 0.086  |
| 0.031  | -0.031 | -0.004 | -0.067 | -0.112 | -0.011 | 0.069  | -0.017 | -0.034 |
| 0.205  | 0.148  | 0.173  | 0.109  | 0.070  | 0.177  | 0.224  | 0.165  | 0.143  |
| 0.064  | -0.046 | -0.012 | -0.069 | -0.094 | 0.001  | 0.009  | 0.023  | -0.042 |
| 0.013  | -0.022 | 0.007  | -0.045 | -0.042 | -0.063 | -0.033 | -0.019 | -0.020 |
| -0.368 | -0.384 | -0.310 | -0.387 | -0.358 | -0.379 | -0.356 | -0.394 | -0.360 |
| 0.046  | 0.029  | 0.086  | 0.022  | 0.061  | 0.039  | 0.017  | 0.088  | 0.046  |
| 0.350  | 0.221  | 0.248  | 0.225  | 0.286  | 0.253  | 0.167  | 0.256  | 0.231  |
| -0.190 | -0.272 | -0.227 | -0.261 | -0.224 | -0.224 | -0.292 | -0.281 | -0.253 |
| -0.089 | -0.183 | -0.113 | -0.180 | -0.136 | -0.130 | -0.194 | -0.087 | -0.159 |
| 0.084  | -0.032 | 0.036  | -0.016 | 0.059  | 0.054  | -0.036 | 0.072  | -0.004 |
| 0.087  | 0.015  | 0.080  | 0.026  | 0.087  | 0.081  | 0.020  | 0.115  | 0.040  |
| 0.327  | 0.222  | 0.309  | 0.252  | 0.315  | 0.300  | 0.242  | 0.336  | 0.261  |
| 0.627  | 0.497  | 0.540  | 0.503  | 0.588  | 0.557  | 0.486  | 0.637  | 0.513  |
| 0.290  | 0.201  | 0.253  | 0.200  | 0.300  | 0.245  | 0.207  | 0.311  | 0.218  |
| 0.112  | 0.010  | 0.102  | 0.030  | 0.134  | 0.072  | 0.055  | 0.121  | 0.047  |
| 0.442  | 0.332  | 0.434  | 0.336  | 0.458  | 0.397  | 0.411  | 0.443  | 0.367  |
| 0.393  | 0.345  | 0.423  | 0.354  | 0.449  | 0.419  | 0.384  | 0.405  | 0.374  |
| 0.137  | -0.006 | 0.102  | 0.049  | 0.120  | 0.090  | 0.088  | 0.078  | 0.048  |
| -0.070 | -0.129 | -0.054 | -0.071 | -0.014 | -0.025 | -0.009 | -0.065 | -0.085 |
| 0.482  | 0.433  | 0.497  | 0.469  | 0.550  | 0.547  | 0.594  | 0.522  | 0.466  |
| 0.939  | 0.923  | 0.946  | 0.909  | 1.016  | 0.997  | 1.066  | 0.953  | 0.926  |

|       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.175 | 0.141 | 0.182 | 0.122 | 0.165 | 0.169 | 0.187 | 0.173 | 0.148 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|

